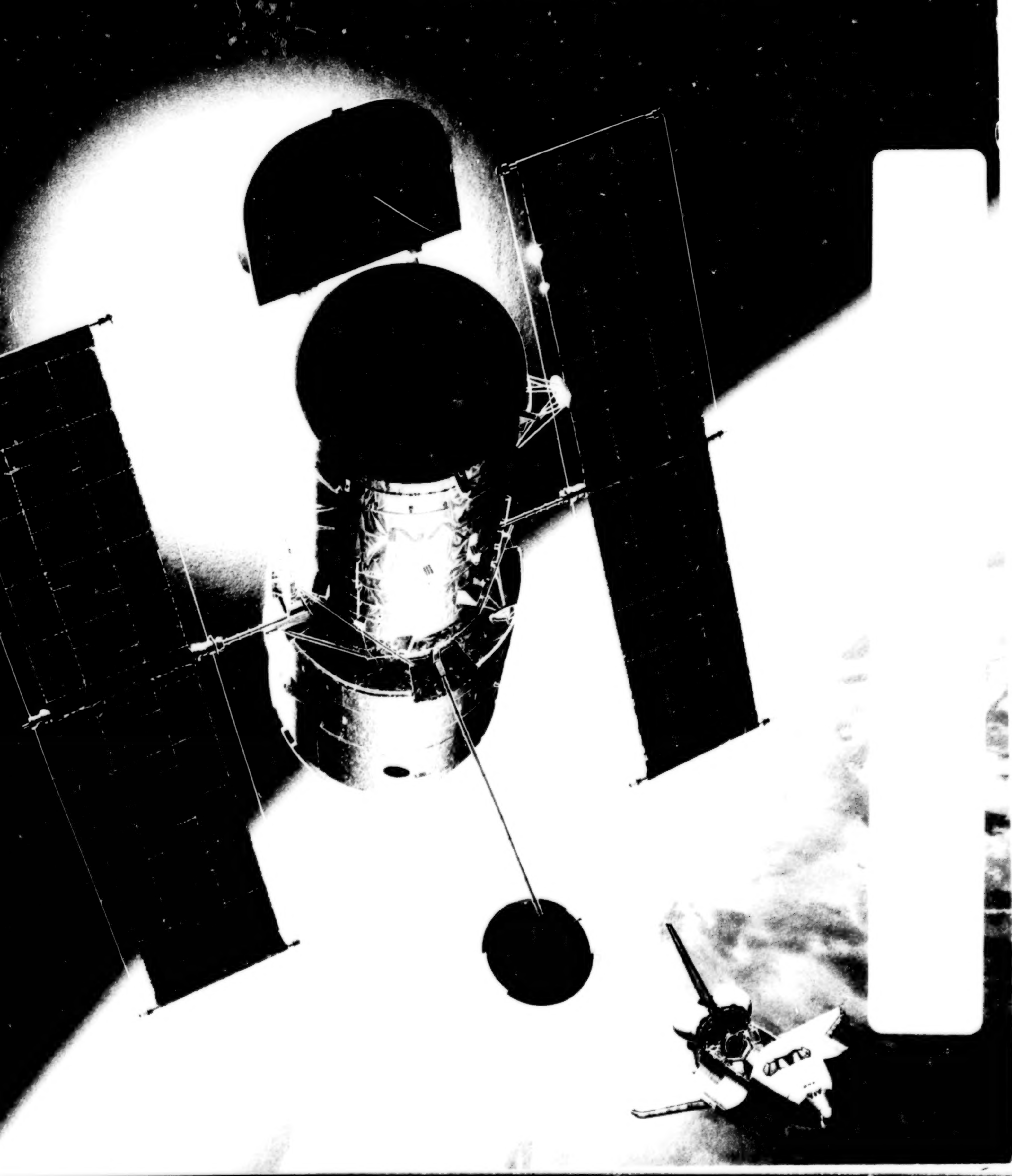
Exploring the Universe with the

Hubble Space Telescope



Exploring the Universe with the

Hubble Space Telescope

Cone Nebula in Monoceros

Anglo-Australian Observatory

NP-126

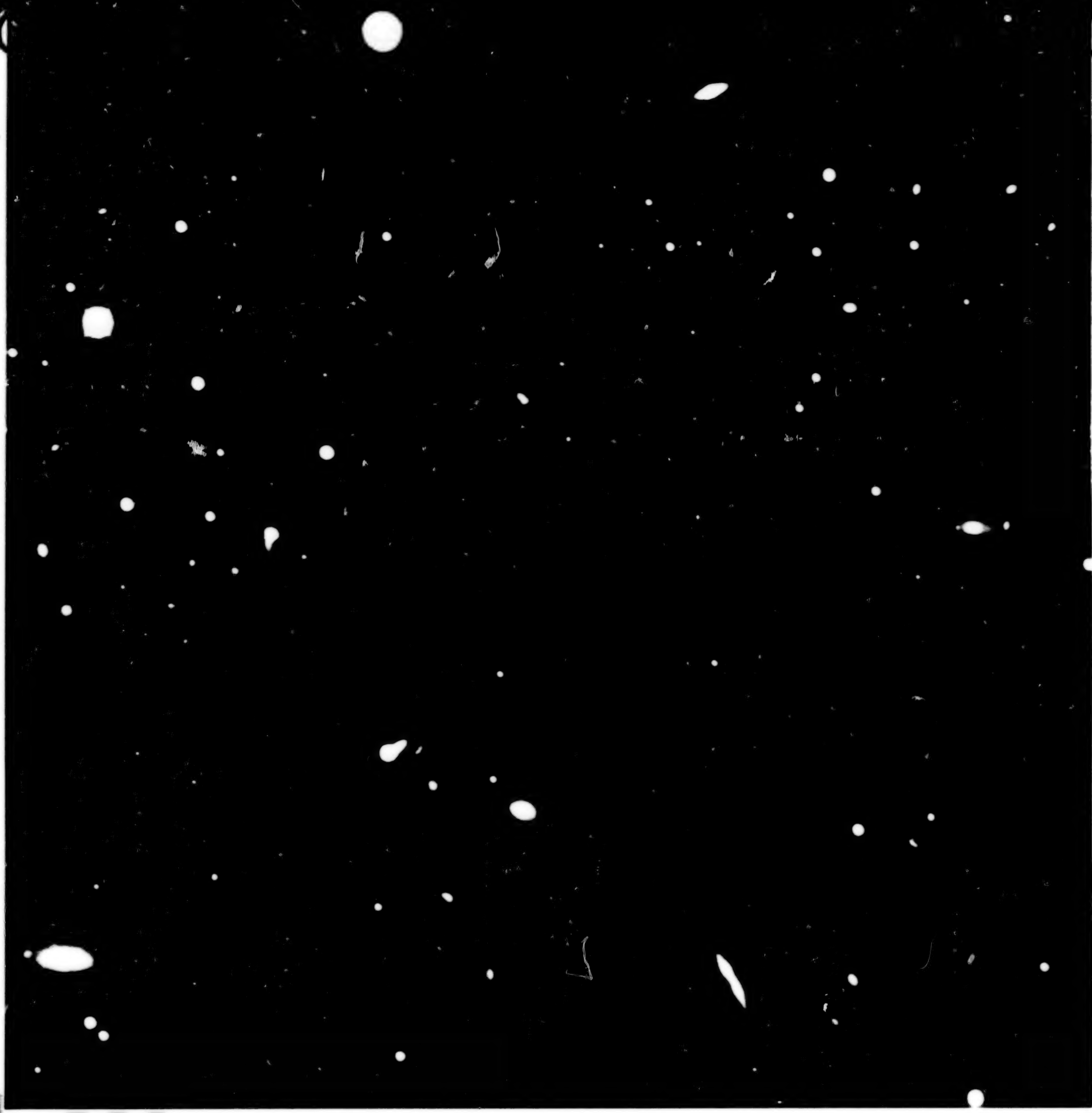
For sale by The Superintendent of Documents, U.S. Government Printing Office, Washington, D.C.

Contents

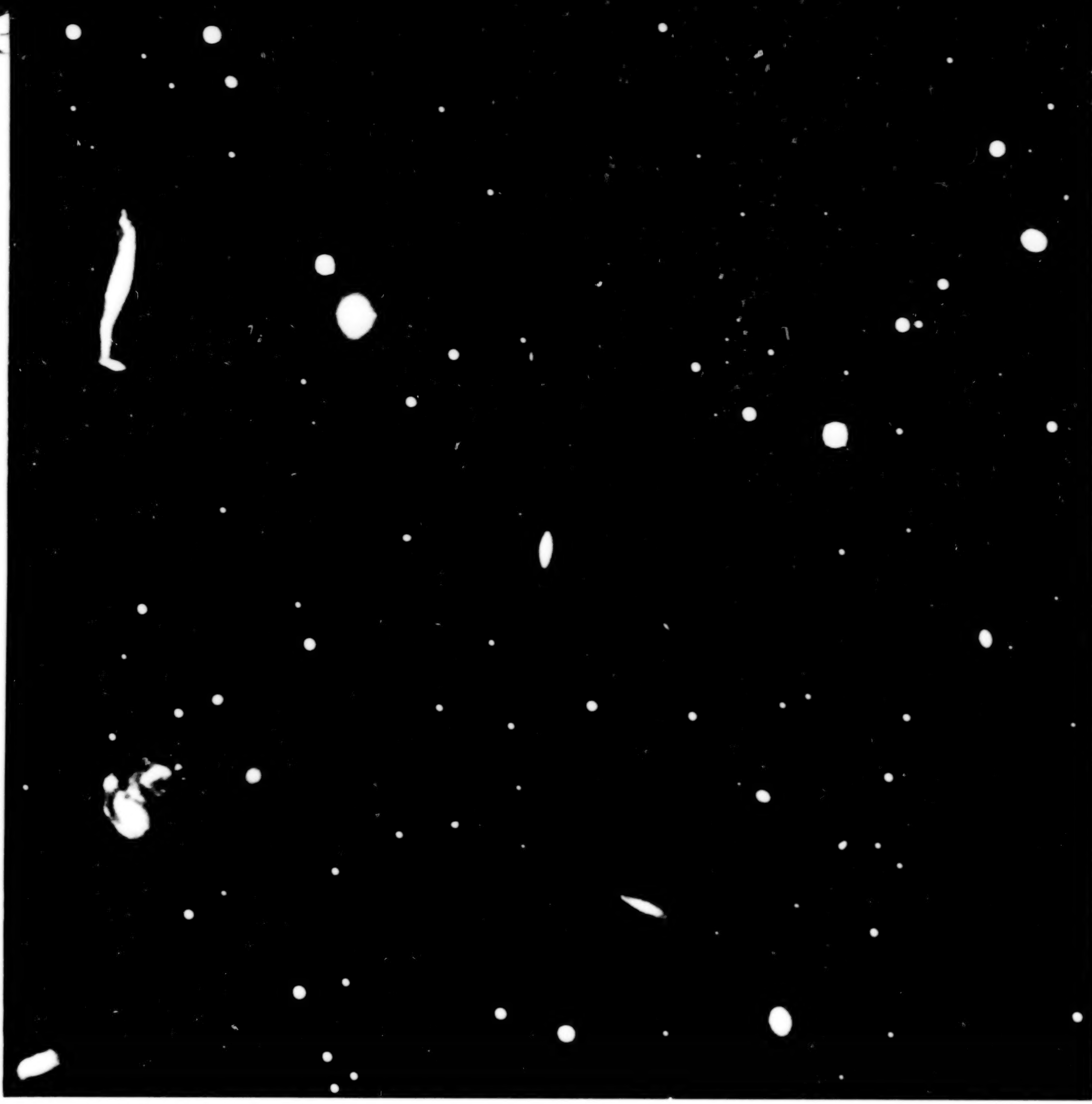
From our home on the Earth, we look out into the distances and strive to imagine the sort of world into which we are born. Today we have reached far out into space. Our immediate neighborhood we know rather intimately. But with increasing distance our knowledge fades, and fades rapidly, until at the last dim horizon we search among ghostly errors of observations for landmarks that are scarcely more substantial.

The search will continue. The urge is older than history. It is not satisfied and it will not be suppressed.

Edwin P. Hubble
Astronomer



We are stargazers.



First Light

In a flash of light, the universe came into being. The dark abyss suddenly filled with energy and matter and motion. From this colossal explosion, an expanding wave of infinite reach surged into time and space. In its wake are strewn the galaxies, stars, and planets—the wondrous creation we call the cosmos.

In those first moments, some 15 billion years ago, events happened so rapidly and forcefully that no evidence lingers, except a faint background radiation. Within the first three minutes, the rudiments of matter appeared in the expanding fire-

The Big Bang (Barron Storey, artist; © National Geographic Society)

ball of intense radiation. About 500,000 years later, hydrogen formed in the cooling maelstrom, then helium and some of the other elements. These atoms began to circulate through the primordial gas and clump together into whirling masses that eventually took shape as galaxies. Exactly when the first galaxies appeared is unknown, but the answer may lie in very distant quasars, more than 10 billion light years from Earth. Within the galaxies, billions upon billions of stars began to shine, and around at least one star a system of planets coalesced, one of which is our home.

The mystery of it all has engaged philosophers and priests, scientists and stargazers from time immemorial. Of course, no one was there to witness the beginning. There are no historical records, no on-the-scene reports. All we have to guide us toward understanding is light. Light is the messenger of creation, a cosmic courier bearing the evidence. The evanescent trail of light from the present back to the first moments carries all the information we will ever have about the origin of the universe.

W

Some 12 to 20 billion years ago, astronomers think a "primeval atom" exploded with a big bang sending the entire universe flying out at incredible speeds. Eventually matter cooled and condensed into galaxies and stars. Planets formed around at least one star. Eons after life began to develop on Earth, humans appeared. If all events in the history of the universe until now were squeezed into 24 hours, Earth wouldn't form until late afternoon. Humans would have existed for only two seconds.

(Jaime Quintero, artist; © National Geographic Society)

To study the universe, its history and its contents, we use whatever we can to catch and analyze light. The most common tool for astronomy is the eye. When we look up at the sky, our eyes receive light, form an image, and send a signal to the brain for processing. Virtually everyone can use this "instrument"; for millennia, it was the only one available.

Unfortunately, the eye is limited in sensitivity and can perceive only the brighter celestial objects. The patient observations of early astronomers yielded an atlas of the universe visible to the unaided eye. They charted the motions of the planets, recorded the positions of many stars, and witnessed a few spectacular explosions of dying stars. However, they had no inkling of the universe we can observe today.

About 400 years ago, Galileo wedded technology and astronomy by using a telescope, a piece of equipment to enhance human vision. His simple arrangement of two magnifying lenses in a tube enabled the first detailed look at some of the objects in the sky and multiplied the number of visible stars. The moon, previously seen as a mottled disk of light and darker patches, suddenly showed a terrain of mountains and valleys. Four of Jupiter's moons were revealed, and stars "so numerous as to be almost beyond belief."

Technology made a world of difference in our ability to form images. The history of astronomy since Galileo's time is a history of technological advances leading to discoveries. Progress in astronomy depends on improved telescopes and detectors to supplement the eye.

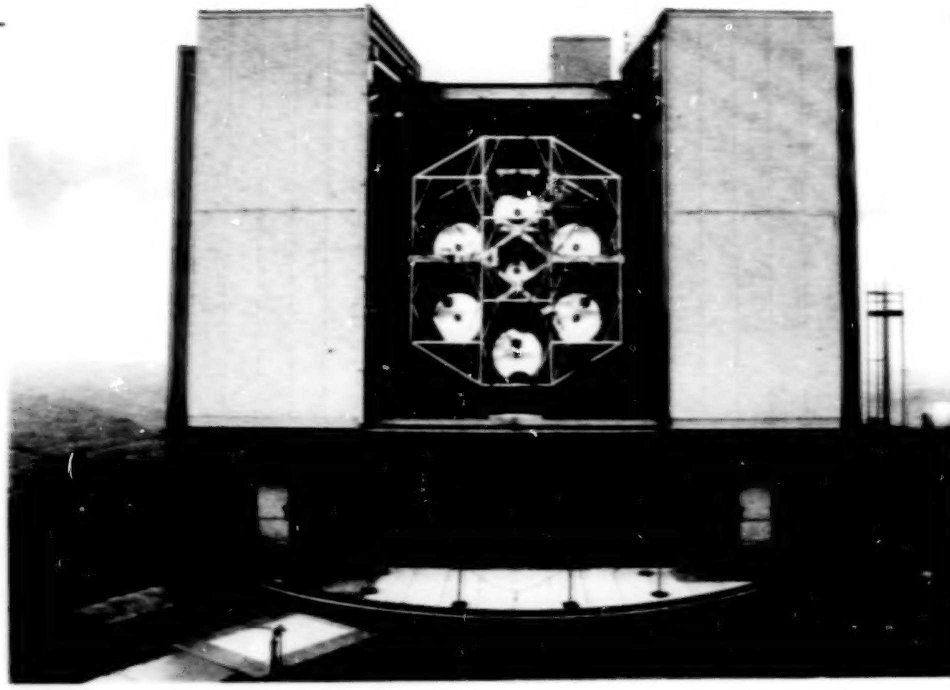
Over the past four centuries, larger and larger mirrors have been constructed for reflecting telescopes. The larger the mirror, the more light is collected and focused into the image. One result is brighter images; objects that were previously below the threshold of detection are now "seen." Another result of using larger mirrors is enhanced fineness of detail (resolution) that can be seen in the image; images are sharper, containing more detailed information.

For collecting light and forming sharper images, bigger is better. Thus, observatories vie for pre-eminence on the basis of mirror size, graduating from mirrors the size of coins and dinner plates to disks as large as backyard satellite dishes. Improvements in mirror grinding, polishing, and reflective coatings also have made a difference.

Amateur astronomers and home-made telescopes
(Dennis di Cicco)

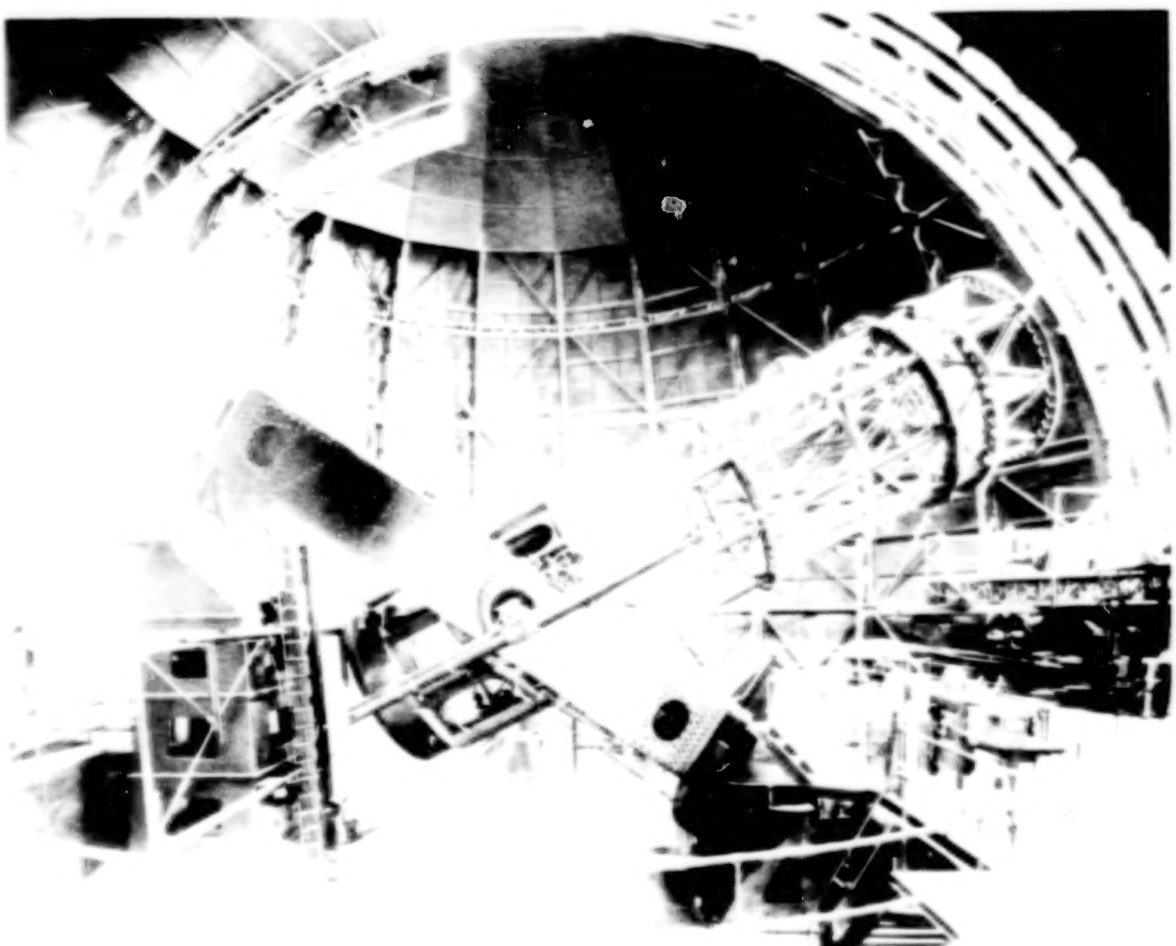
Galileo, credited with first use of the telescope in 1609
(Yerkes Observatory)

Astronomer in observing capsule of the 200 inch Hale telescope



The Multiple Mirror Telescope at Mt. Hopkins, Arizona an innovative design for a large light-collecting surface

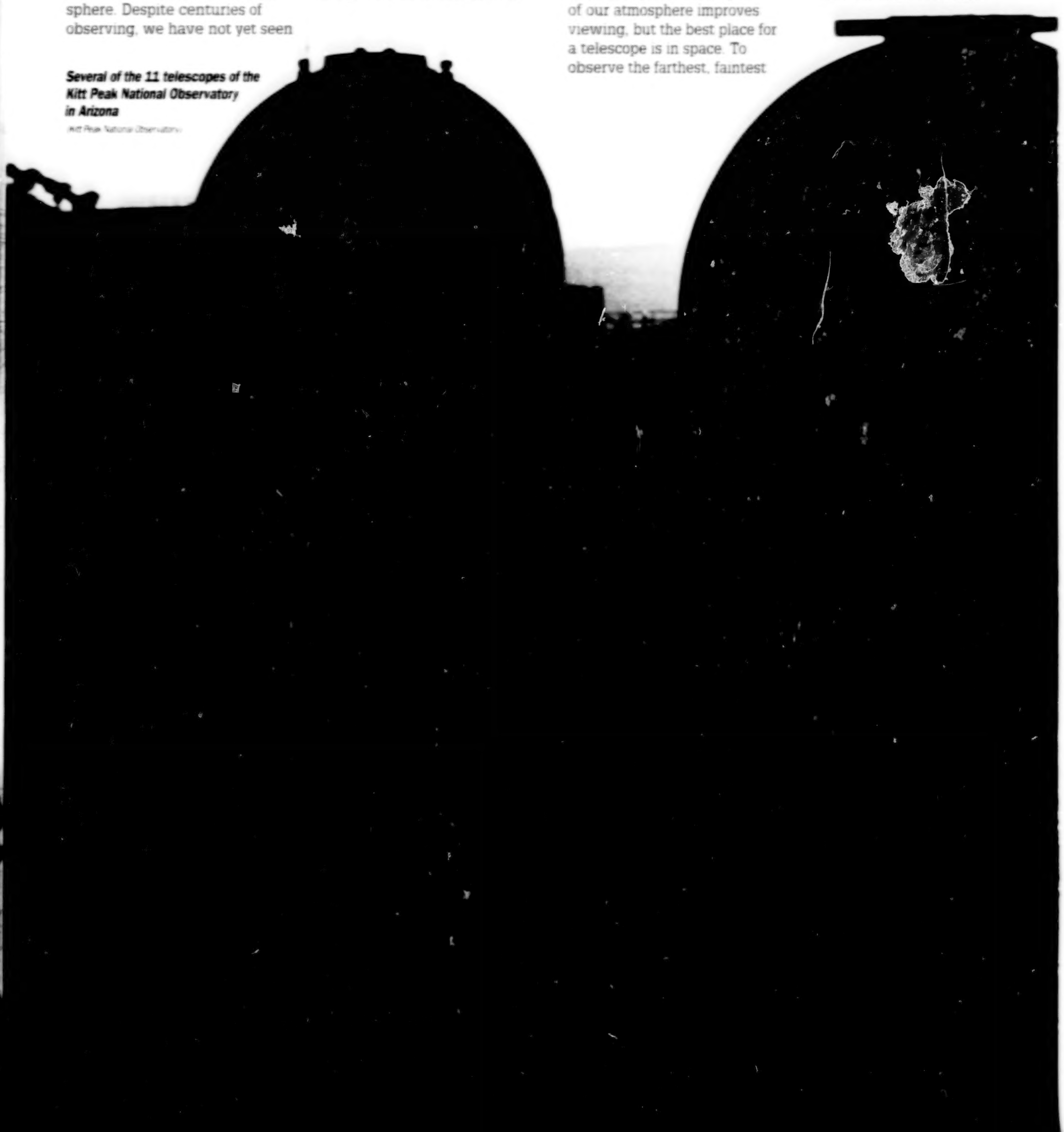
Astronomer Annie Cannon, early 20th century pioneer in spectral analysis



100 inch Hooker telescope at Mount Wilson

Advances in mirror and detector technology yield dramatic improvements in obtaining information about objects in the sky, up to a point. Then astronomers face a barrier that is not affected by bigger, more sensitive telescopes: the atmosphere. Despite centuries of observing, we have not yet seen the universe clearly, because we are looking up through a hazy shroud of gases around our planet. As light from celestial objects is bent, scattered, and absorbed by passage through our turbulent atmosphere, images are distorted, blurred, and dimmed. From the ground, we can distinguish objects well only to a distance of some two billion light years, although the universe probably extends ten times farther.

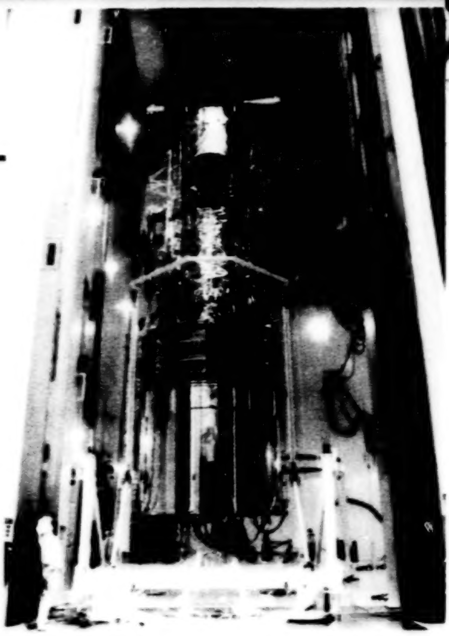
Placing telescopes on high mountain peaks above part of our atmosphere improves viewing, but the best place for a telescope is in space. To observe the farthest, faintest stars and galaxies in as much detail as possible, we must lift our telescopes into orbit beyond the turbulent, obscuring atmosphere. If it were practical, most telescopes would be located in space, where viewing conditions are most favorable.



Several of the 11 telescopes of the Kitt Peak National Observatory in Arizona

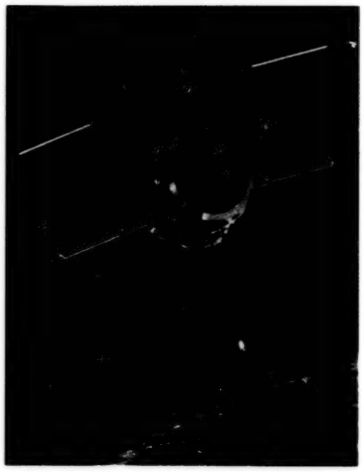
(Kitt Peak National Observatory)

The Hubble Space Telescope during assembly and testing
(Lockheed Missiles and Space Company)



Astronomers have dreamed of placing a large visible-light telescope into space, but only recently has the technology been developed to make this possible. The Space Shuttle is powerful enough to carry into orbit a large telescope comparable to some of the best telescopes on the ground. Furthermore, the Shuttle can take a maintenance crew to an orbital observatory for repairs and servicing. For the first time in the space age, we have a warranty for a long operational life. Space telescopes are expensive; to get the most science from our investment, we must be able to use them for many years.

The Hubble Space Telescope is the realization of that dream: a virtually perfect mirror, superior detectors, and an orbit above the atmosphere. This is the instrument that will reveal what lies beyond our present power to see. Until now, advances in telescope capability have occurred in fairly small steps; mirror sizes have doubled or tripled, and improvements in sensitivity and resolution have been measured up to 50 times better. With a telescope in space, we leap to new capabilities at least 10 times better than optical telescopes on the ground. The Hubble Space Telescope is the best optical telescope in the world, a precious international resource for satisfying our human need to know the cosmos.

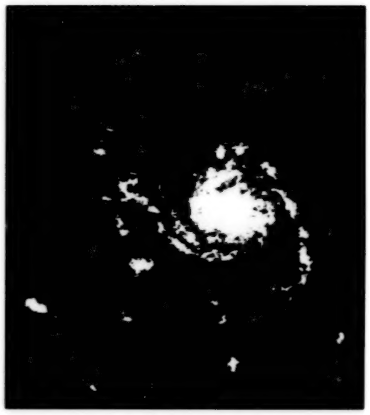


Observation Strategy

For generations, humans have looked at the same sky, asked the same questions, and pressed against the same physical barriers to observation. How large and how old is the universe, and how do we measure it? What are the objects we see there? How do galaxies form and evolve? What is the life cycle of stars? Do other planets exist? Is there life elsewhere in the universe? At first, our attempts to explain the cosmos took the form of myths and folklore, which have now given way to scientific theories and observations.

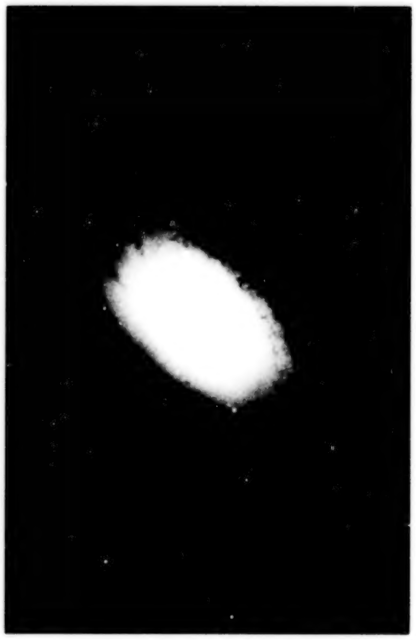
Of all the observatories that exist in the world, only the Hubble Space Telescope can answer some of the most perplexing astronomical questions. The Hubble Space Telescope can detect objects 12 to 14 billion light years distant as clearly as a much larger telescope on the ground can detect objects a mere 1 to 2 billion light years away. Images will be at least 10 times sharper in clarity than any others, and light emitted very early in the life of the universe, 30 to 50 times fainter than our current threshold, will be easily detected.

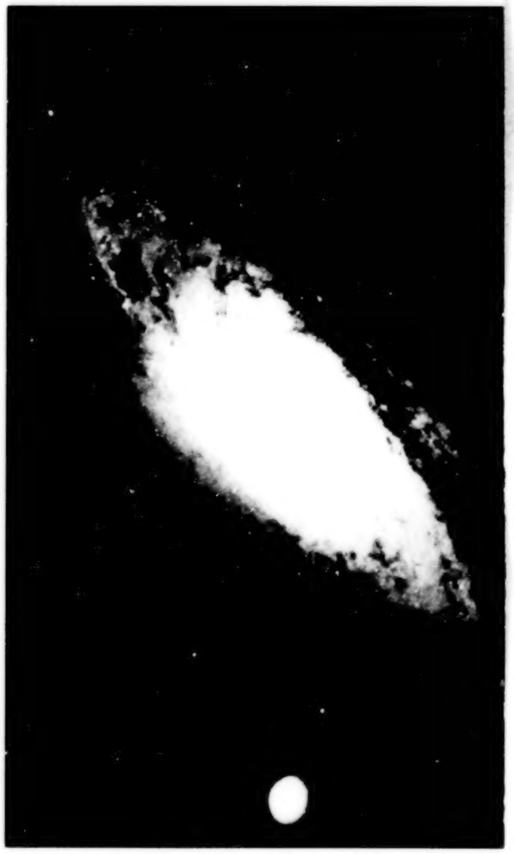
The observing strategy takes advantage of these unique abilities to see objects farther away and with greater clarity than any other telescope. The highest priority investigations are those that cannot be performed from the ground; we do not know exactly what these exploratory observations will reveal. Some are focused where our knowledge is quite limited, at objects beyond 10 billion light years, toward the "edge" of the observable universe. Research requiring extraordinarily precise position measurements, now possible for the first time, is scheduled early in the

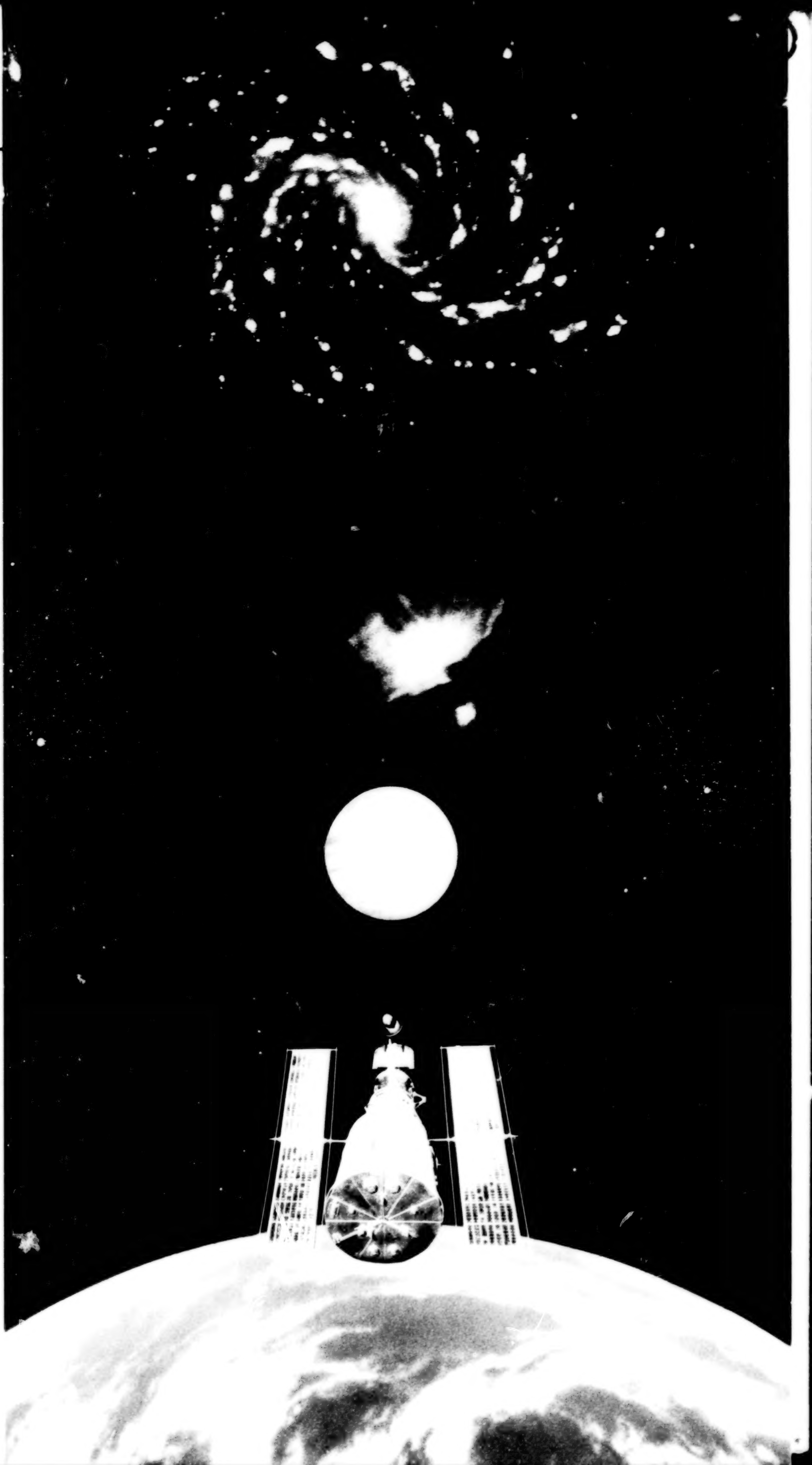


These images of M101 galaxy in Ursa Major, one 10 times sharper than the other, simulate the improvement in detail expected in images from the Hubble Space Telescope. (California Institute of Technology)

In longer time exposures, more light is collected and resulting images have more detail. These images of two galaxies in Andromeda resulted from observations lasting 1 minute, 5 minutes, 30 minutes, and 45 minutes, respectively. The Hubble Space Telescope will be able to obtain detailed images of faint objects with shorter exposures than observatories on the ground. (Kitt Peak National Observatory)







The Hubble Space Telescope may answer questions about all classes of astronomical objects, from neighboring planets and stars to the most distant galaxies and quasars.

Edwin P. Hubble

1889–1953

As a child, Edwin Powell Hubble wandered the Kentucky countryside where he grew up, observing the habits of birds and animals. As an adult, he scrutinized the stars and galaxies.

Although Hubble was always interested in science, he did not settle on the profession of astronomy immediately. In 1910, he received an undergraduate degree from the University of Chicago, where he also lettered in basketball and almost became a professional boxer. Instead, he studied law under a Rhodes scholarship at Oxford, passed the bar, and practiced law briefly and halfheartedly. He reported that he "chucked the law for astronomy, and I knew that even if I were second-rate or third-rate, it was astronomy that mattered."

Hubble completed graduate studies at the Yerkes Observatory of the University of Chicago, where he began his examination of spiral nebulae. He earned his doctorate in 1917 and was invited to join the Mount Wilson Observatory in Pasadena, California, but Hubble did not yet undertake the studies that made him famous. Answering the call to World War I, he enlisted in the infantry, telegraphing observatory personnel, "Regret cannot accept your invitation. Am off to the war."

Niels Bohr Library, American Institute of Physics

Two years later he finally began working with the tool that would enable him to make great discoveries—the 100-inch reflector at Mount Wilson, at the time the largest telescope in the world. Except for four years of service in World War II, Hubble was devoted to astronomy until his death in 1953.

Hubble's patient, painstaking observations revealed a much larger universe than anyone had imagined. He was enchanted by dim, foggy patches called "nebulae," the Greek word for cloud. One called Andromeda was the most spectacular nebula observed during the early decades of the century, but telescopes were not powerful enough to see if it harbored any stars like the vast stellar populations of the Milky Way. Since the 18th century, scientists had argued whether these areas were "island universes," separate galaxies, or simply nebulae in our galaxy. Was the Milky Way the only galaxy? Was it the center of the universe?

In 1924, Hubble ended the debate when he reported stars in the outskirts of Andromeda and found Cepheids, stars that reveal their distance by the way their light varies. Careful observations of the Cepheids enabled him to measure the distance to Andromeda, far too many light-years away to be in our galaxy. He classified the galaxies, grouping them by sizes and shapes, and established that many other nebulae were also galaxies even more distant than Andromeda. Hubble measured the depths of space out to 500 million light years, distances farther than any previous surveys.

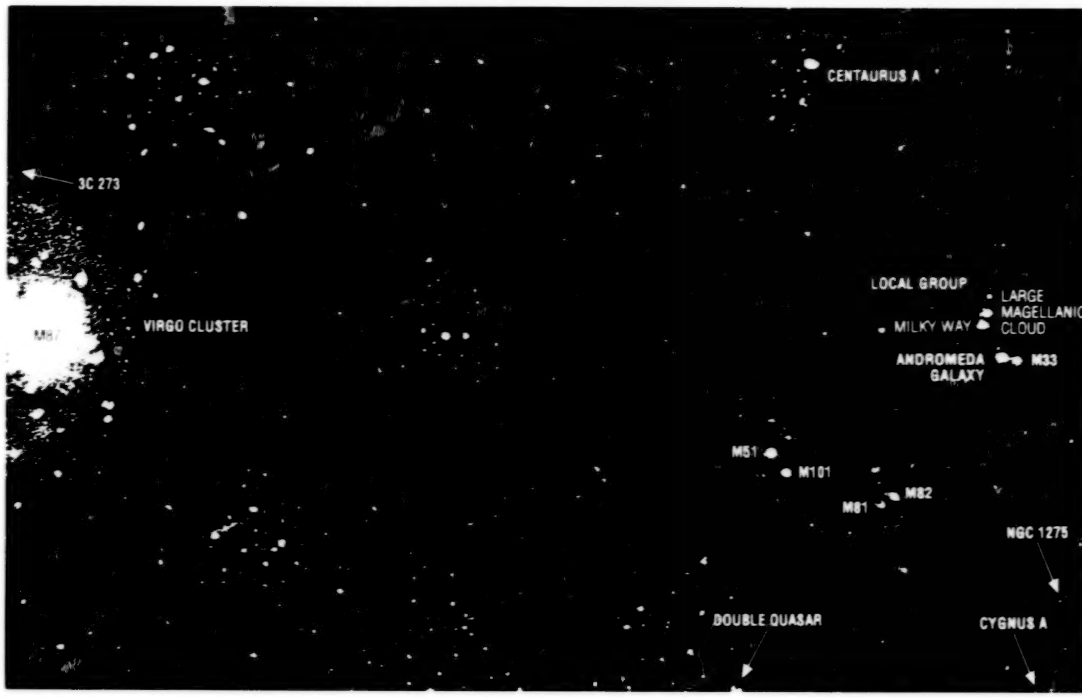
As he continued to study galaxies, he concluded that they were moving away from Earth at velocities proportional to their distances. This supported the concept that the universe originated in a cosmic explosion, and all the matter in the universe was expanding from the site of an initial Big Bang. The galactic survey resulted in Hubble's law: the more distant the galaxy from Earth, the faster it moves away.

Of course, if all the galaxies originated from one explosion, residents of other galaxies would see the same thing: a universe of fleeing galaxies with more distant ones moving more rapidly.

Hubble found that the ratio of the velocity of receding galaxies to their distance from Earth is constant (the Hubble constant), a significant astrophysical number still not calculated with certainty today. Unfortunately, as the distances to objects increase, astronomers are overwhelmed with uncertainties: distances are hard to measure. Current estimates of the Hubble constant, and thus the rate of expansion of the universe, differ by a factor of two. More powerful telescopes are needed to make more precise measurements and determine whether the universe will expand forever or halt and perhaps reverse.

The Hubble Space Telescope will build on Hubble's research, measuring distances with greater accuracy than ever before possible. It is fitting that this premier space observatory is named for the American astronomer whose work revolutionized modern astronomy. Hubble's research proved that larger, more powerful telescopes are needed to see more of the universe. He assisted in the design of the 200-inch Hale telescope at Mount Palomar near San Diego and made the first observations with it. When asked what he expected to find with the new telescope, he said, "We hope to find something we hadn't expected." With the Hubble Space Telescope, this quest continues.

Edwin P. Hubble at the 48-in Schmidt telescope at Palomar Observatory



Better "roadmaps" are needed for accurate distance measurements to galaxies much farther away than these neighboring galaxies.

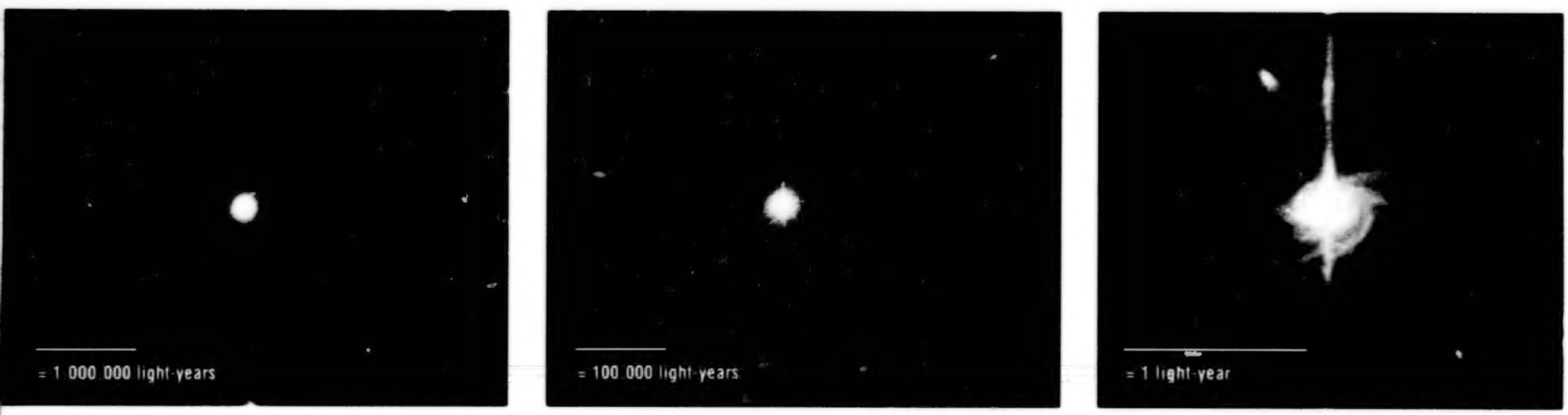
How do we measure the universe?

When the United States decided to send men to the moon, scientists and engineers lacked an essential bit of information: the exact distance to the destination. At that time, no one knew precisely enough for navigation purposes just how far away the nearest celestial body was located.

Although the distances to some stars and galaxies are published as so many light years, these measurements in the celestial atlas are, in reality, estimates. The actual distance scale beyond the Milky Way has never been precisely determined; current estimates are so uncertain that galaxies may be twice as far away as we think, or only half as far.

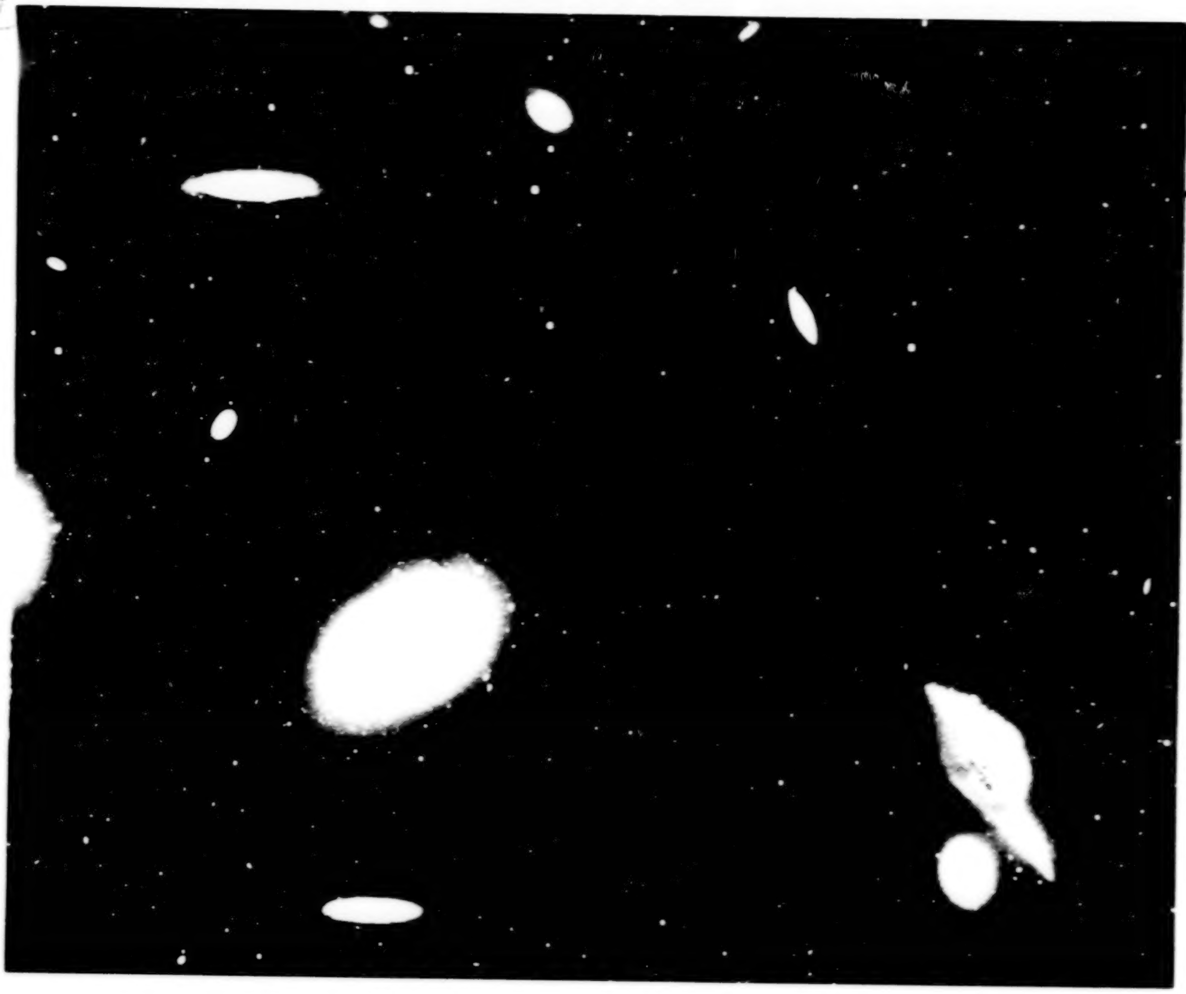
Distance is crucial to almost every problem in astronomy, especially issues in cosmology about the origin and age of the universe. Astronomers need to know how far away the various bright and dim objects are and how far apart they are. A precise measurement of distance is also the basis for establishing an accurate value of the Hubble constant, a measure of the age and rate of expansion of the universe.

A high-priority project is to use the Hubble Space Telescope to refine the distance scale of the universe and to calculate a more accurate value of the Hubble constant. With its ability

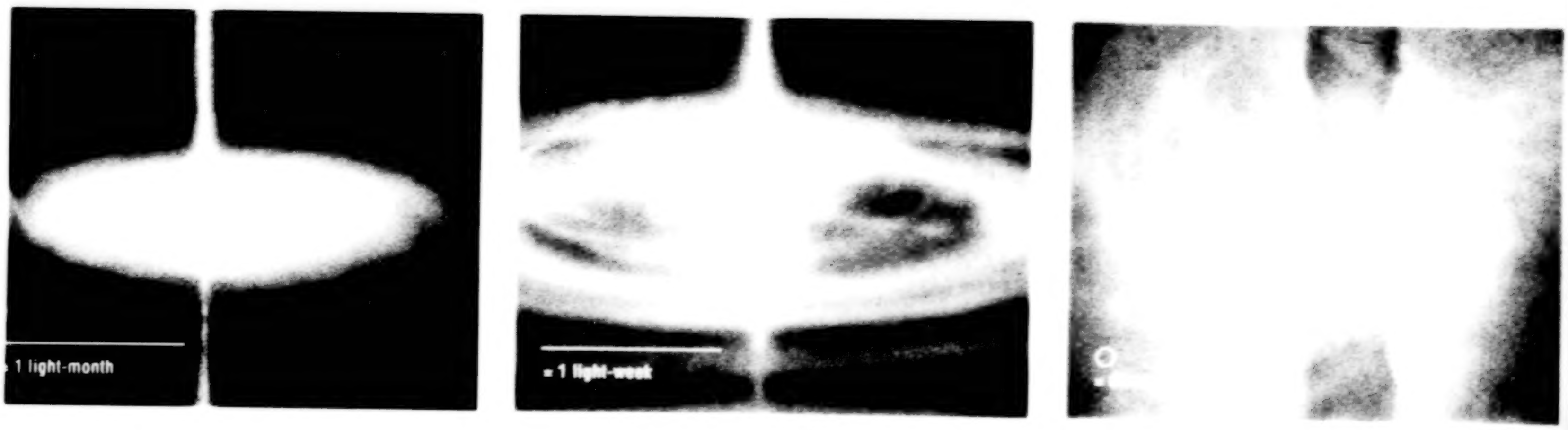


The Hubble Space Telescope will resolve some of the detail that is usually lost over vast distances.

Cepheid variables are common reference points for astronomical measurements. The difference in brightness of these Cepheids in the Andromeda galaxy (between the dashed lines) is evident.



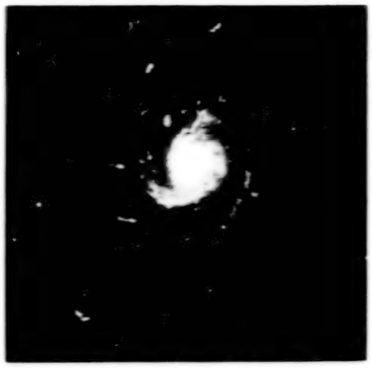
More accurate measurements of distances to objects in the Virgo cluster of galaxies, 60 million light years from our galaxy, will give scientists better "yardsticks" for calculating precise distances to objects much farther away.

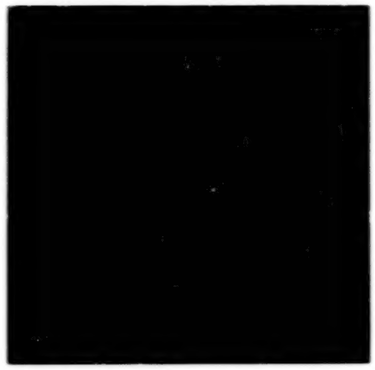


What are quasars, active galaxies, and other exotic objects?

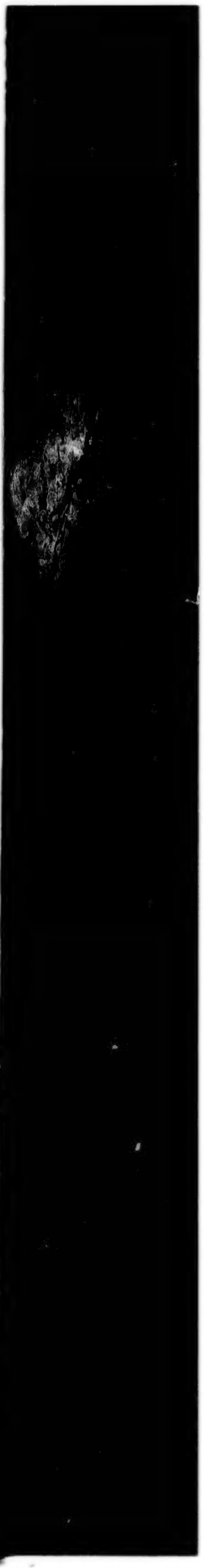
into space is looking back in time, we see quasars today as they appeared billions of years ago; they may not even exist now. Quasars may be explosions that precipitate galaxies, the violent first step in an evolutionary process that gradually results in a normal galaxy like our own.

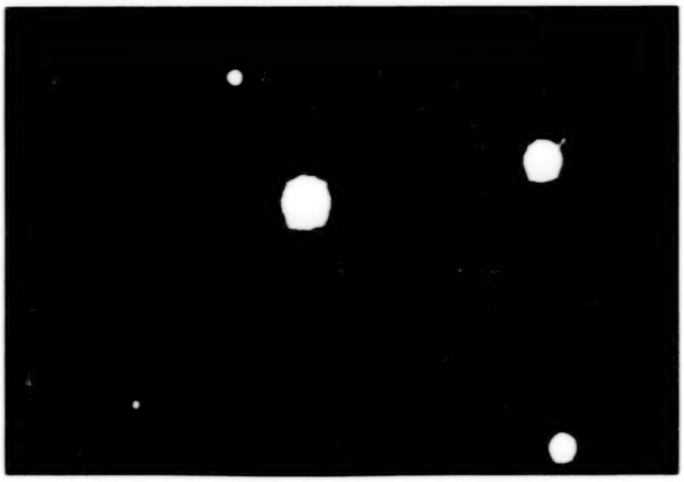
In some galaxies, the central region emits extraordinarily intense and variable radiation. It is thought that quasars or black holes hidden in these active galaxies may be the power source. High-resolution studies of the centers of galaxies by the Hubble Space Telescope should reveal this mysterious phenomenon.





Observations in different radiation bands reveal different features, as shown in these two images of the M101 galaxy, one in visible light (left) and the other in ultraviolet (right). Only the higher-temperature objects and areas appear in ultraviolet images, while the cooler ones disappear. Kitt Peak National Observatory, visible; NASA Goddard Space Flight Center, ultraviolet





Quasar 3C 273 in Virgo is a mysterious object that may radiate 100 times more light than the brightest ordinary galaxy.
Kitt Peak National Observatory

Some quasars and other objects emit perplexing jets of radiation.
Adolph Schaller, artist

The existence of black holes, which may devour matter from nearby stars, is theorized but not yet confirmed.
Don Dixon, artist

How do galaxies form and evolve?

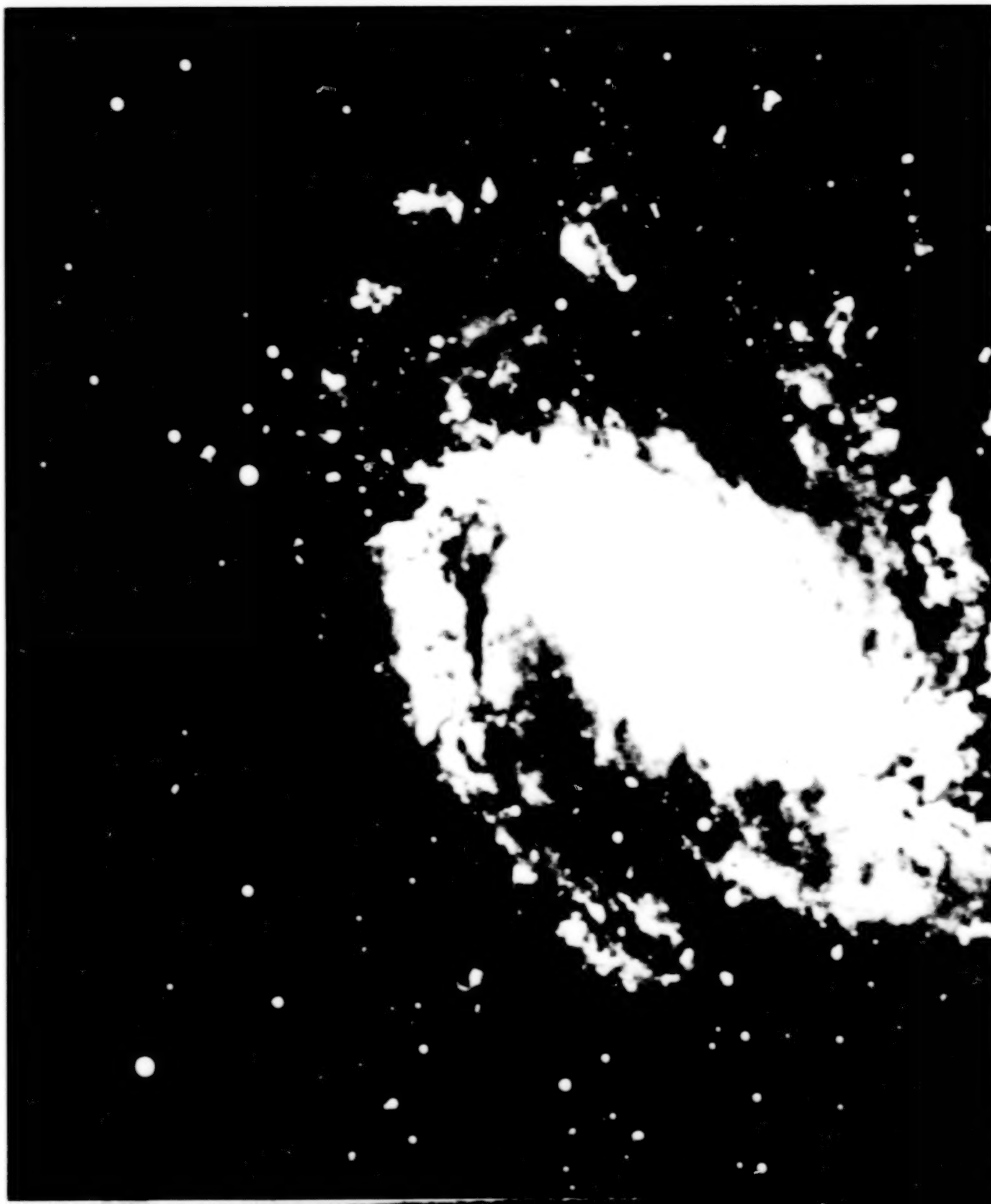
There are an estimated 100 billion galaxies in the universe, and we know only one reasonably well: our own Milky Way. As recently as the 1920's, when Edwin P. Hubble corrected the record, no one knew with certainty that other galaxies existed. Since then, galaxies have been identified, labeled, and placed in a classification scheme based on their structure or other features, but only a fraction of the total population of galaxies has been sampled.

Galaxies are intrinsically interesting evidence of the origin of the universe, for it is thought that they were the first objects to form after the cosmic "Big Bang." They seem to be the basic building blocks that give structure to the universe. Curiously, there is little evidence that new galaxies are forming today.

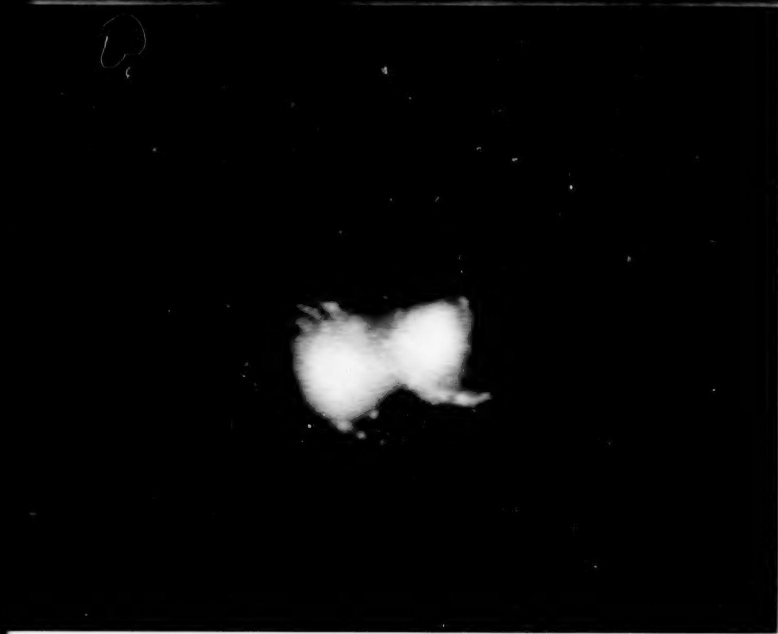
Astronomers are eager to see the farthest (youngest) galaxies out toward 15 billion light years, for these should reveal the conditions under which the universe began to take shape. To understand how the universe evolved, astronomers need to study as many galaxies of as many types and ages as possible. Today, only the 20 nearest galaxies have been studied in any detail; these are contemporaries of the Milky Way, similar in form and content. A more thorough census is required.

With the very sensitive Hubble Space Telescope, astronomers will be collecting information about galaxies during the early stages of their formation and adding new galaxies to the list of those available for study. In addition, they will get a more detailed look at some puzzling phenomena, such as active galaxies that produce extraordinary energy compared to typical galaxies. It is thought that the nuclei of such galaxies may harbor quasars or black holes, which are not yet well understood. With the improved resolution of this telescope, astronomers will be able to peer into the crowded centers of galaxies to find what lies hidden there.

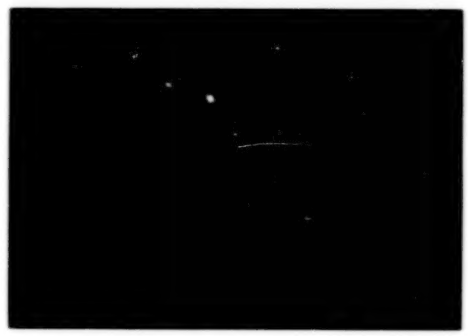
Celestial merger: galaxies may collide and interact, exchanging matter and resulting in the formation of new stars.



Spiral galaxy M83 in Hydra

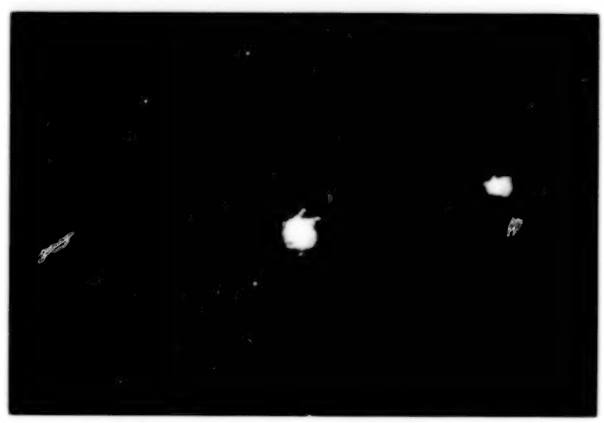


The Hubble Space Telescope will be used to observe a variety of galaxies of different types, distances, and ages:



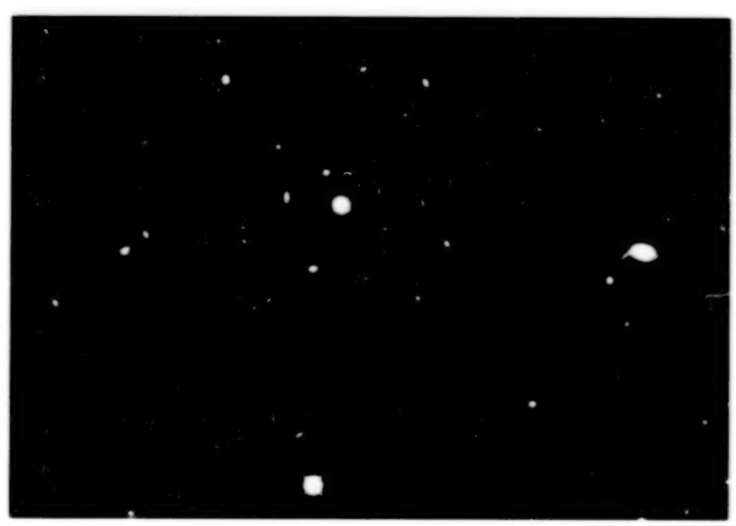
Small Magellanic Cloud

Royal Observatory



Whirlpool Galaxy in Canes Venatici

Palomar Observatory, California Institute of Technology



Cluster of galaxies in Coma Berenices

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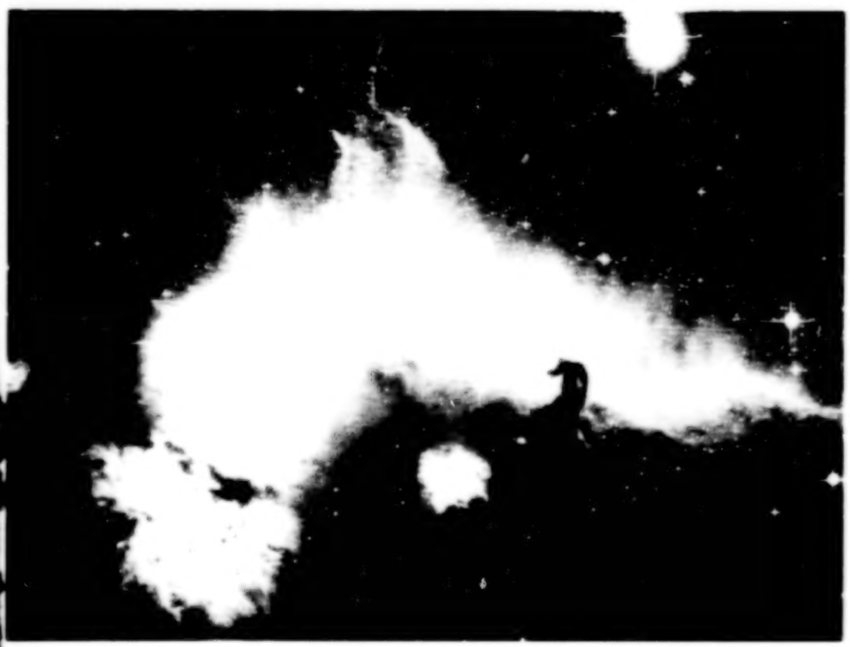
What is the life cycle of stars?

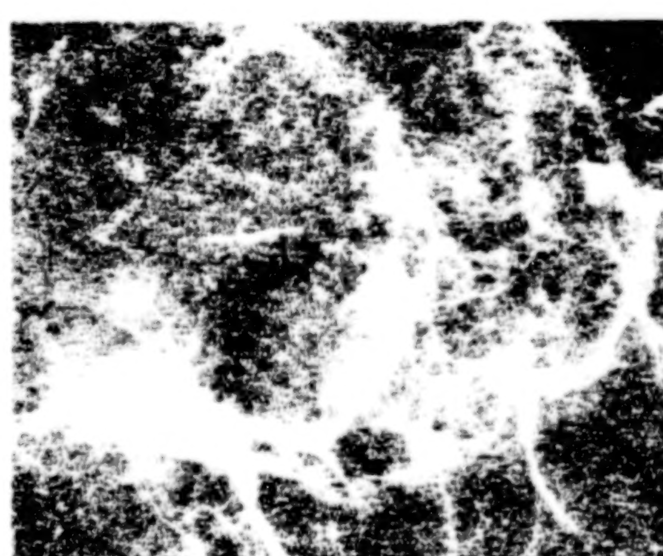
Nebulæ are often called stellar nurseries, because new stars form in these glowing clouds of dust and gas.



Horsehead Nebula in Orion is an opaque cloud of dust that absorbs light from stars beyond it.

The Pleiades are a cluster of about 3,000 stars in Taurus; the Hubble Space Telescope will be able to resolve stars in more distant and very dense clusters.

A supernova is a stellar explosion that temporarily may outshine all other stars in its galaxy. An interesting target of observation is the supernova discovered in 1987 in the nearby Large Magellanic Cloud



Supernova remnants hollow shells of gas may linger for centuries as glowing evidence of the death of a star

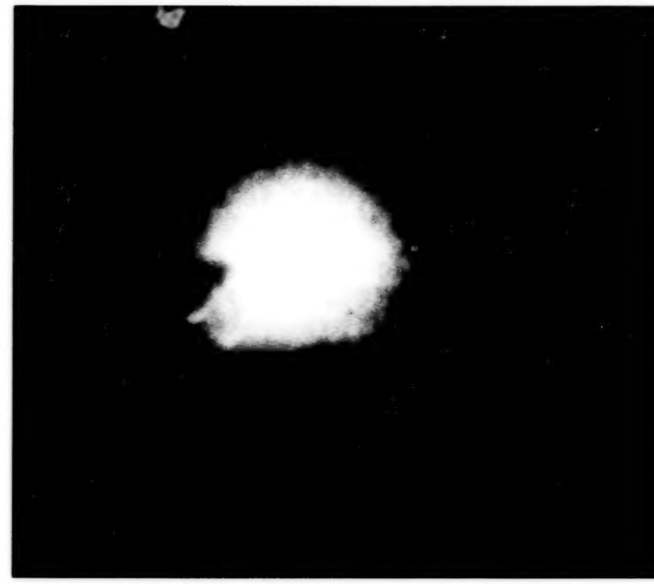
Do other planetary systems exist?

The Hubble Space Telescope will enable studies of the planets in finer detail than is possible from the ground.

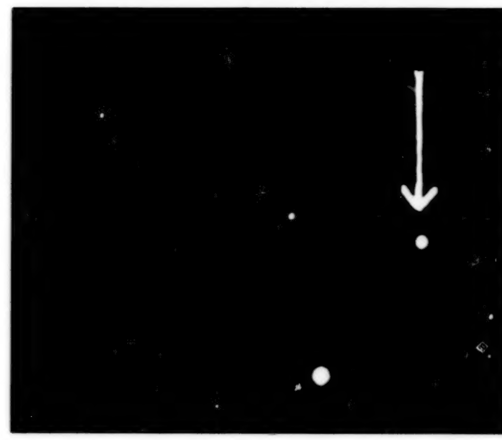
A close-up view of Jupiter and its moons Io (left) and Europa (right) comparable in detail to expected Hubble Space Telescope images. This image was obtained at a distance of 20 million km (12.4 million mi) by the Voyager spacecraft.

One of the best images of Jupiter from a telescope on the ground.

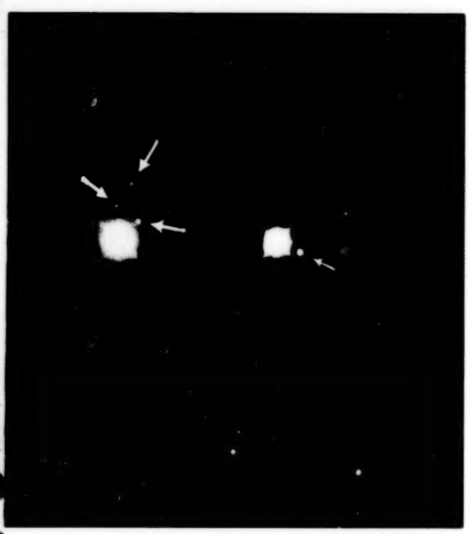
The Hubble Space Telescope will give us a front row view of the fascinating worlds of our solar system.



Voyager image of Neptune from 82 million km (51.5 million mi) similar in detail to a Hubble Space Telescope image
(NASA)



Pluto, never yet seen in detail
(Palomar Observatory, California Institute of Technology)



Uranus and Neptune observed from Earth
(Lick Observatory)

A Voyager image of Saturn from 13 million km (8 million mi), comparable in resolution to Hubble Space Telescope imagery
(NASA)

A typical ground-based image of Saturn
(Palomar Observatory, California Institute of Technology)

Using the

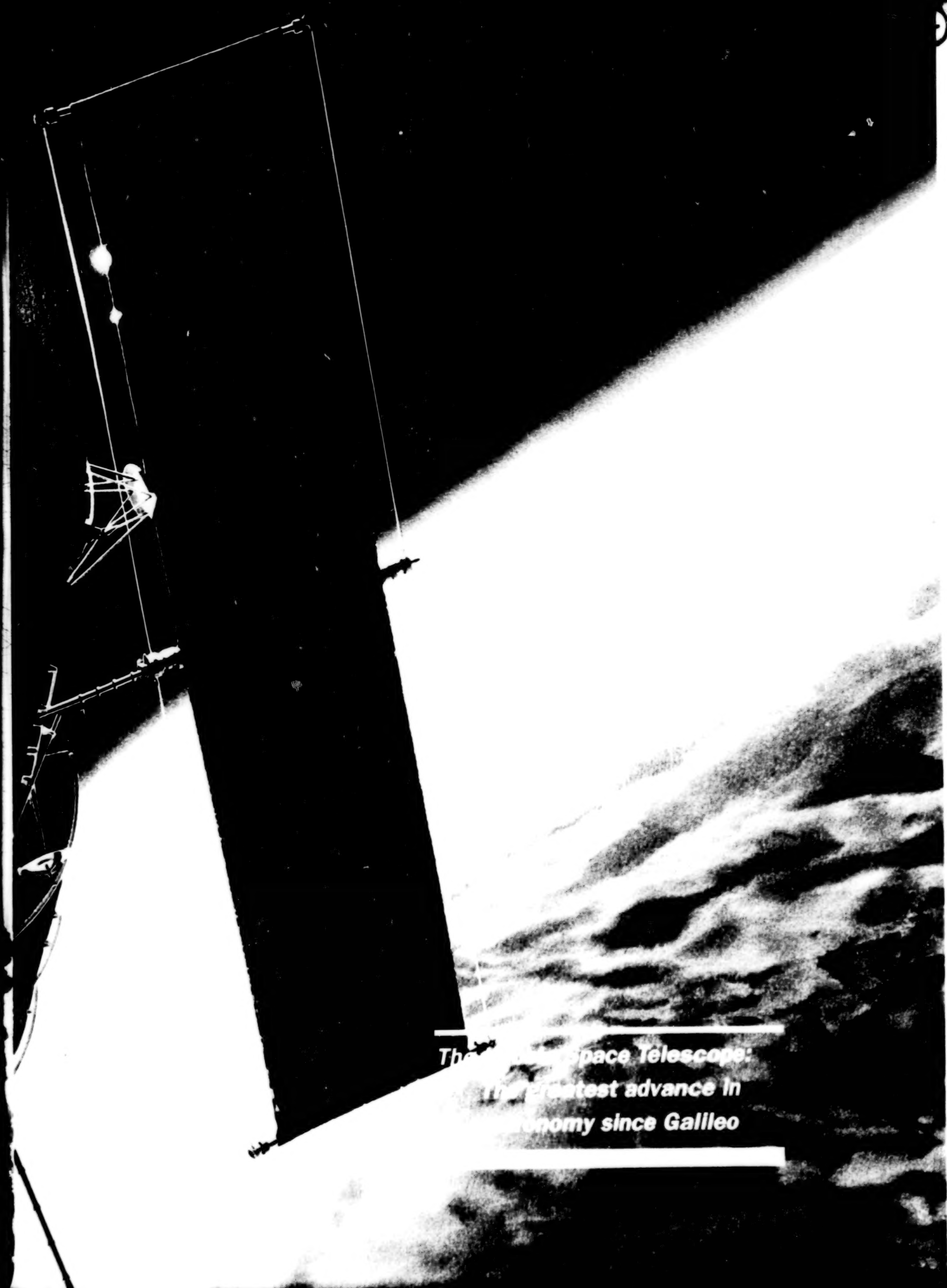
Hubble Space Telescope

Like polished sterling, the Hubble Space Telescope gleams against the velvet drape of night. Its design is sleek: a long case, covered with shiny foil, not unlike an amateur telescope or kaleidoscope in its simple contours, though much larger. The distinctive features marking it as a spacecraft are two solar panels and two fragile antennas. It could be a modern sculpture, a silvery winged creature embarking on a flight into the cosmos.

Orbiting some 370 miles above us, this telescope is an extremely sensitive light catcher, ready for the arrival of infinitesimal bits of visible, infrared, and ultraviolet energy that have traveled billions of years through space. The light detected today originated so long ago and so far away that its arrival is greeted with curious anticipation. This welcome messenger can reveal to us what the universe is like, how it began, and how it changes.

The jewel of the telescope, the 8-foot primary mirror, is deep inside the protective case. The mirror is a marvel of technology: large but lightweight, its pure aluminum reflecting surface thinly coated with transparent magnesium fluoride. To focus faint light as precisely as required, the mirror had to be virtually perfect, and it is. No bump or ripple on its polished surface deviates more than one millionth of an inch from an ideally perfect curve; no mirror has ever been more finely polished or more evenly coated. If the Earth were as smooth, the highest peak and the deepest valley would vary from the surface by less than three inches.

Hubble Space Telescope (Paul Hudson, artist)


Space Telescope:
advance in
since Galileo

Control room in the Space Telescope Operations Control Center at NASA's Goddard Space Flight Center in Maryland

NASA

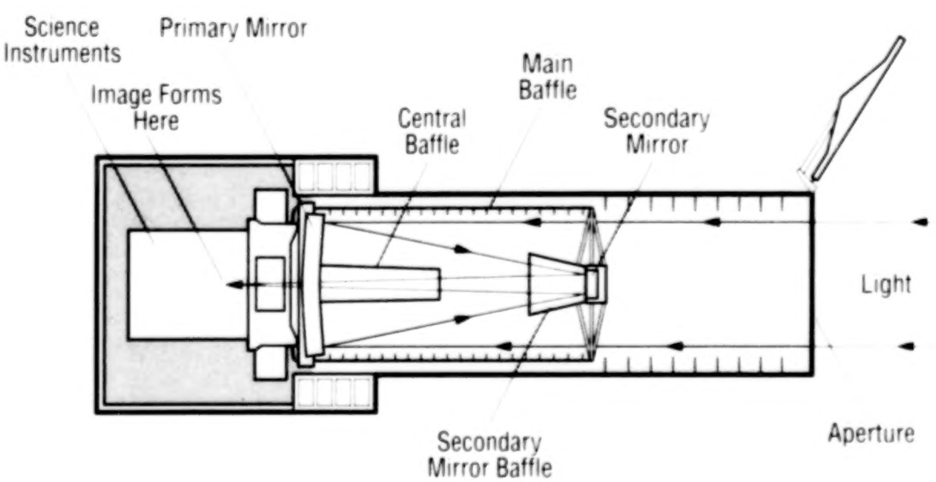
The Hubble Space Telescope is an observatory unlike any astronomical observatory on Earth.

Light entering the telescope strikes the primary mirror, is reflected forward to the secondary mirror where it is reflected again, returning down the telescope and through a hole in the primary mirror to the focal plane, where the image forms. There, detectors record images or analyze the incoming ultraviolet, visible, or infrared light. These focal plane instruments are crucial to the observatory; without them, the advantage of the perfect mirror and vantage point above the atmosphere would be wasted. The detected light is converted into electronic signals and transmitted by relay satellite to ground stations. There the data are processed by computers and reconstructed as images for astronomers to study.

The Hubble Space Telescope is an observatory unlike any astronomical observatory on Earth. Some of the differences are obvious. It doesn't have the familiar dome shape of observatory buildings, because it needs no protection against weather. It has peculiar features like solar panels, to generate electrical power, and communications antennas, to receive and transmit information. The telescope is remotely controlled by operators hundreds of miles below it and, at times, half a world away. It operates around the clock, day and night, seven days a week, year after year, unaffected by clouds and weather. Visibility is always perfect.

More subtly, the Hubble Space Telescope represents a revolutionary shift in the way most astronomers do their work. During the deployment, operational, and servicing phases of its mission, the telescope is handled differently than is customary for a ground-based telescope. With the Hubble Space Telescope, astronomical research reaches maturity in the space age.

The Hubble Space Telescope will be delivered to orbit by the Space Shuttle. Initial checkout will occur while the telescope is attached to the Shuttle; then it will be released for years of operation in space.



Path of light through the telescope to the detectors

Space Telescope in Orbit

First Days

Slowly and gently, the telescope is lifted from its cradle in the payload bay of the Space Shuttle. Attached to the spidery remote manipulator arm, the 43-foot telescope clears the bay door and is held overboard for a methodical checkout before release. There is no ribbon-cutting ceremony, no cornerstone to set in place, no speech under a dome. Instead, opening night activities proceed in a brisk, businesslike fashion. Only five people are present.

Inside the Shuttle, an astronaut intently watches through a window and operates the mechanical arm to position the telescope for the first stages of its deployment. The commander is on duty to oversee activity, while the pilot maneuvers the Shuttle. Two other crew members stand by, prepared to go to work outside the cabin if some problem arises.

Meanwhile, scores of personnel at ground control centers monitor every electronic signal and issue commands as the telescope is being prepared to operate in space. The mood is vibrant; scientists, engineers, managers, and VIPs concentrate on video screens and adjust their headsets, listening quietly to terse status reports: "Solar arrays deployed... power-up sequence initiated..." The two solar arrays gradually unfurl, and then the two antennas fold out. The Shuttle eases away to a respectful distance, where it hovers until the initial checkout is complete.

Observing with the Hubble Space Telescope

In the nearby media center, journalists keep vigil, their editors and producers saving front pages and prime time for on-the-scene reports. Across the country at NASA centers and aerospace firms, thousands of people involved in the project know that today is the red letter day, the culmination of years of effort. Around the world, astronomers await word that the new observatory is deployed, promising new vistas for the most ancient science.

Actually, ground controllers have been "talking" to the telescope since four hours after launch, waking the various systems and readying them to be turned on. For launch, the telescope is dormant; its activation in orbit is a methodical procedure that lasts about three days for initial deployment and several months for full checkout. This verification sequence carefully brings the telescope to full operational status.

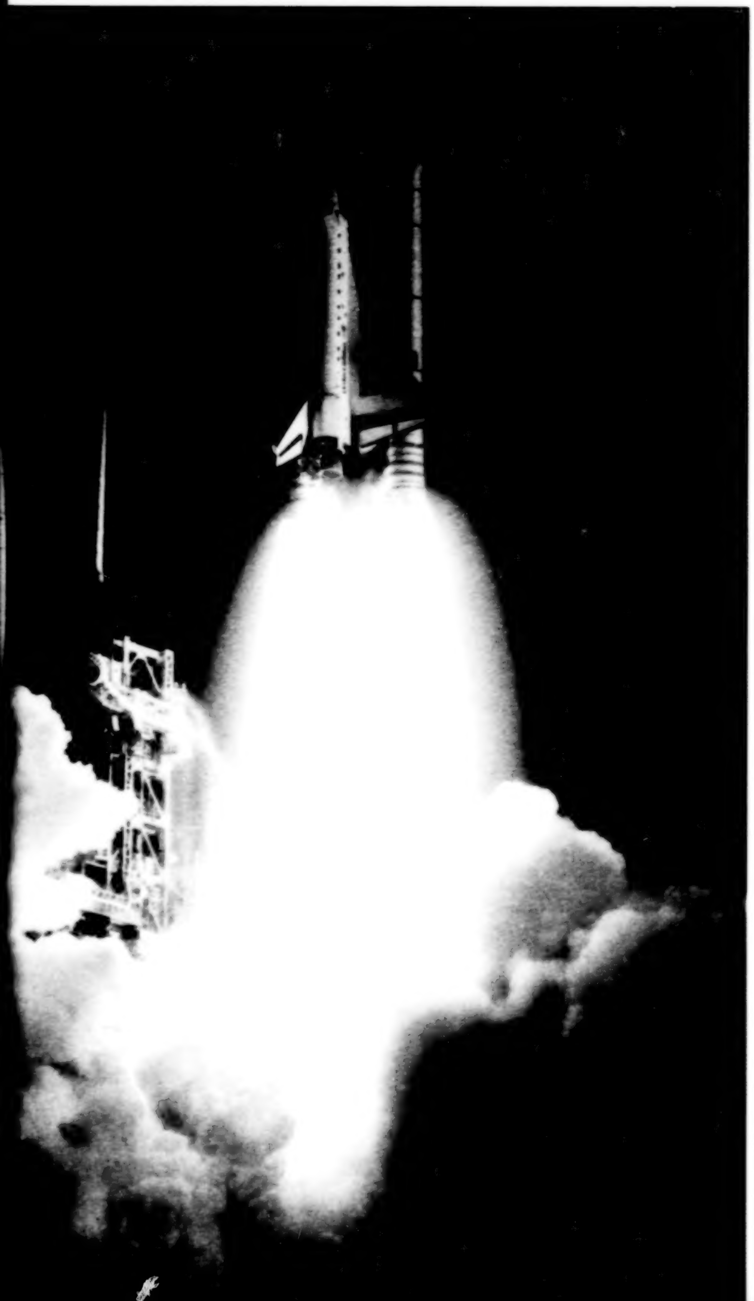
About 24 hours after launch, the telescope is unplugged from the Shuttle power supply and begins operating on its own battery power. It is then lifted from the bay by the robot arm and held outside the Shuttle during preparations for release. The solar arrays must be deployed promptly to activate the telescope's internal power system, and the antennas must be unstowed for two-way command and data flow. By the second day in orbit, the telescope is ready to be released.

For the next several hours, the ground control teams put the telescope through its paces, gradually bringing it up to full power, turning on its "housekeeping" systems for pointing and attitude control, loading the computer memories, and testing the telemetry. These activities verify that everything is working properly as the telescope adjusts to the space environment.

The third and fourth days are dedicated to testing the telescope's ability to move and point accurately, to acquire guide stars and targets. Then the alignments of the mirrors and scientific instruments are checked, and calibration tests are run. About two weeks into the mission, checkout of the cameras and other scientific instruments in the focal plane begins.

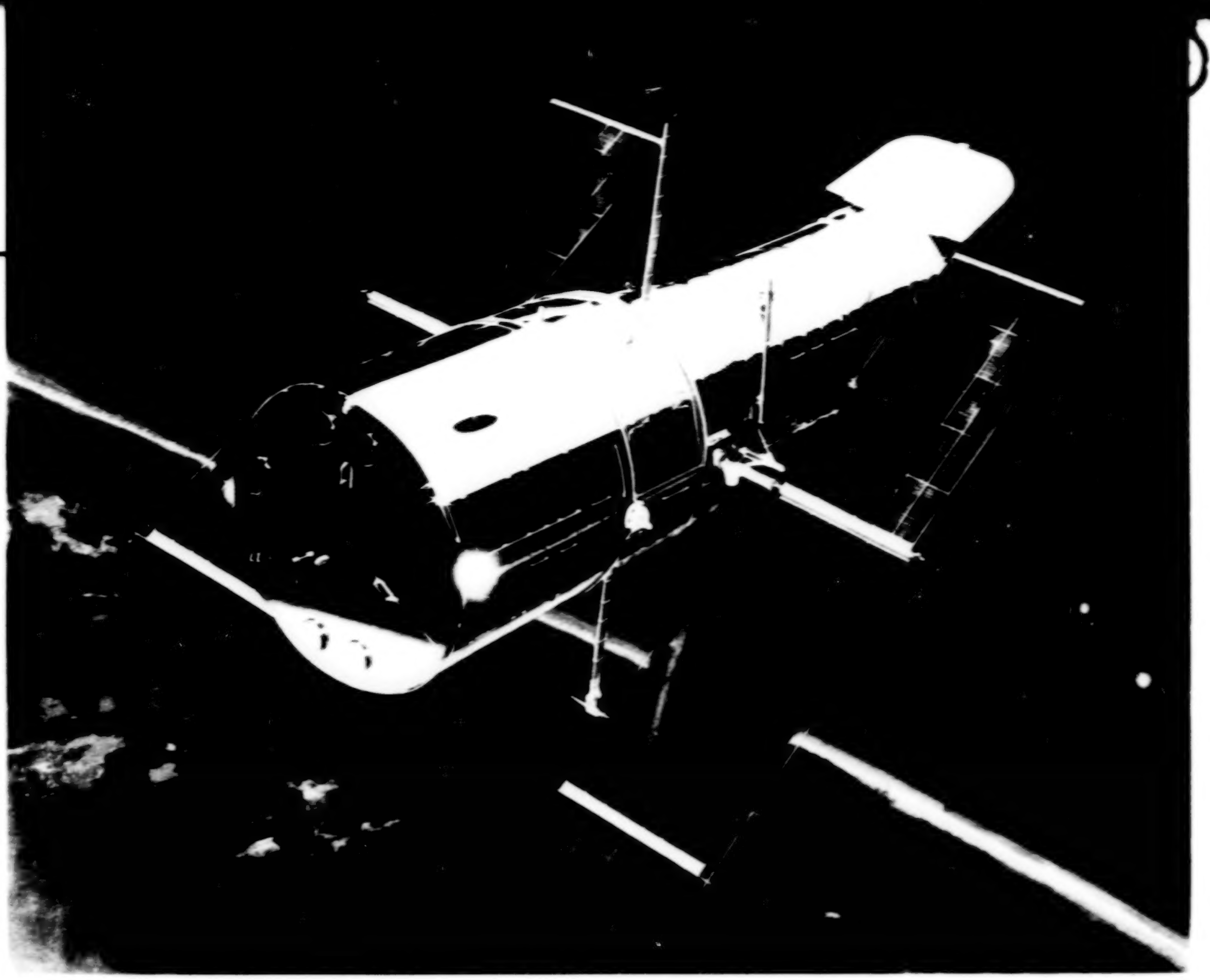
Checkout is a time for patience. A full six months have been allocated for meticulous verification that all systems and instruments are functioning properly. This period will be punctuated by some actual observations, but the observatory's schedule will not be turned over to the scientists until the checkout is complete.

Two NASA centers share responsibility during this trial period. The Marshall Space Flight Center in Huntsville,



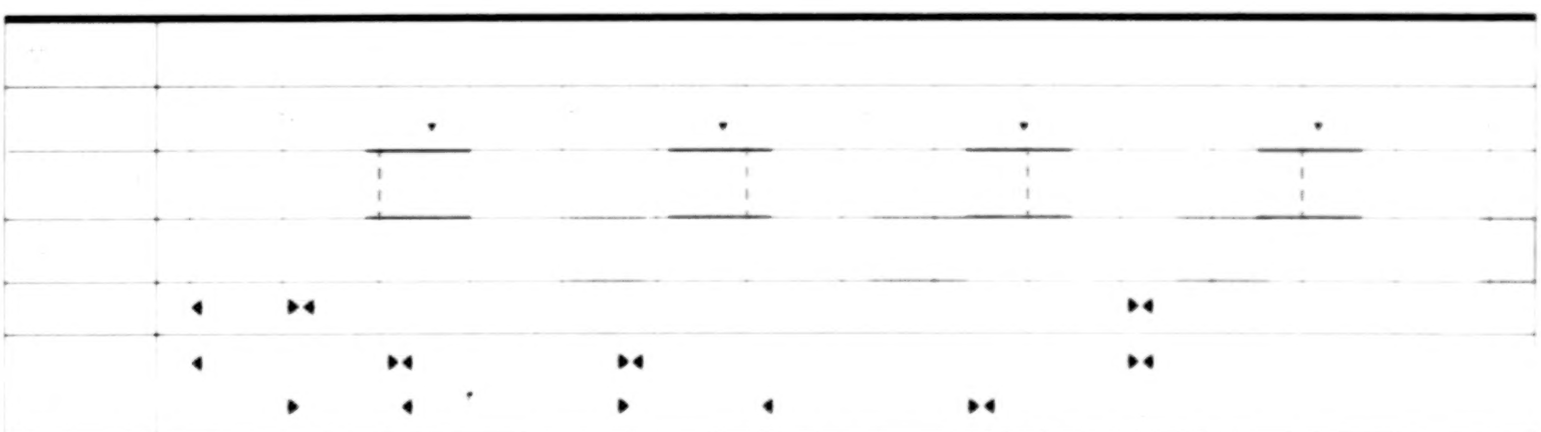
Astronauts working in the aft flight deck of the Space Shuttle deploy the Hubble Space Telescope.

NASA



Hubble Space Telescope in orbit

The first several months in orbit are reserved for checkout and verification of the telescope before science operations begin.



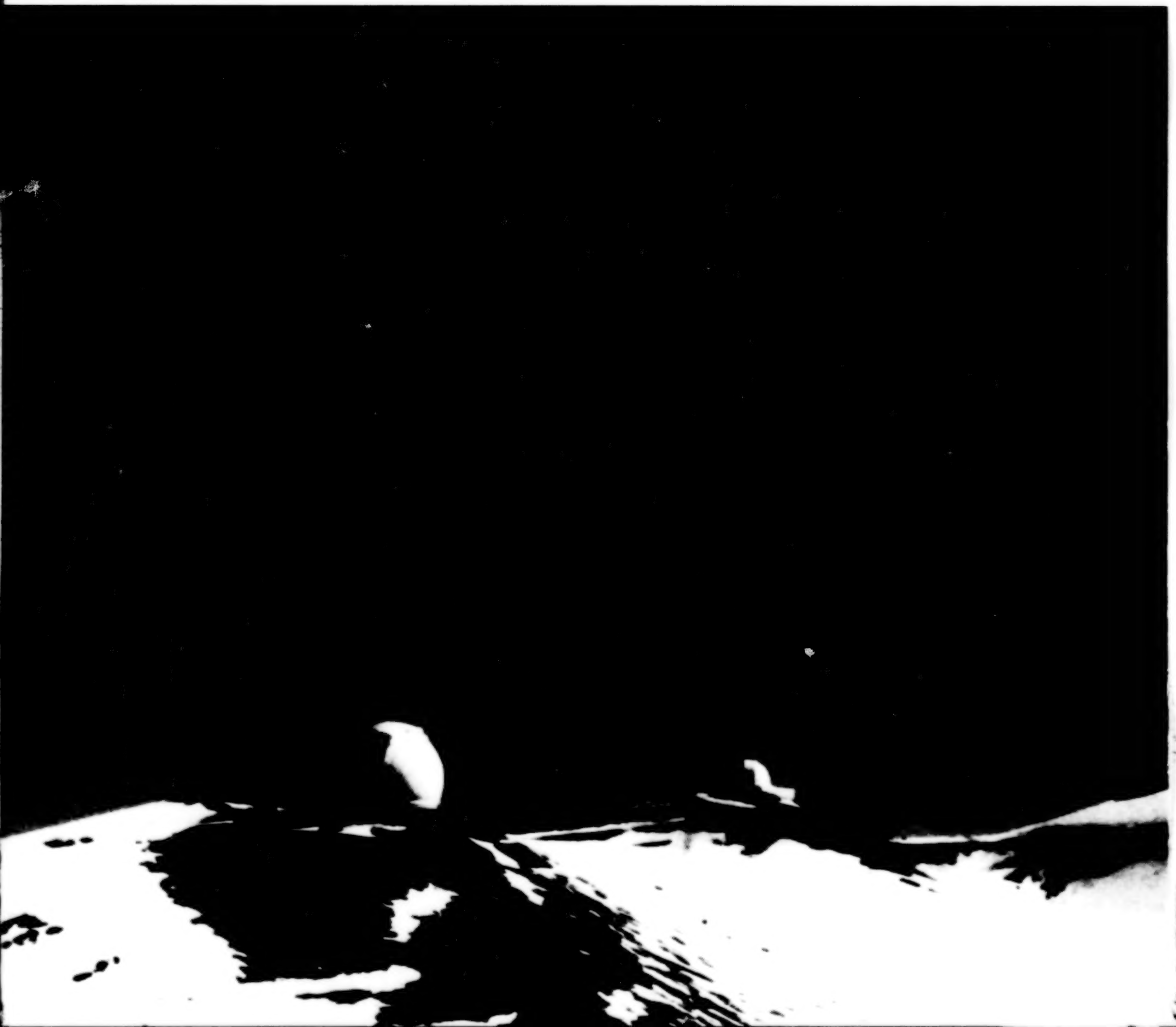
Segment of the deployment mission timeline

Day-to-Day Operations

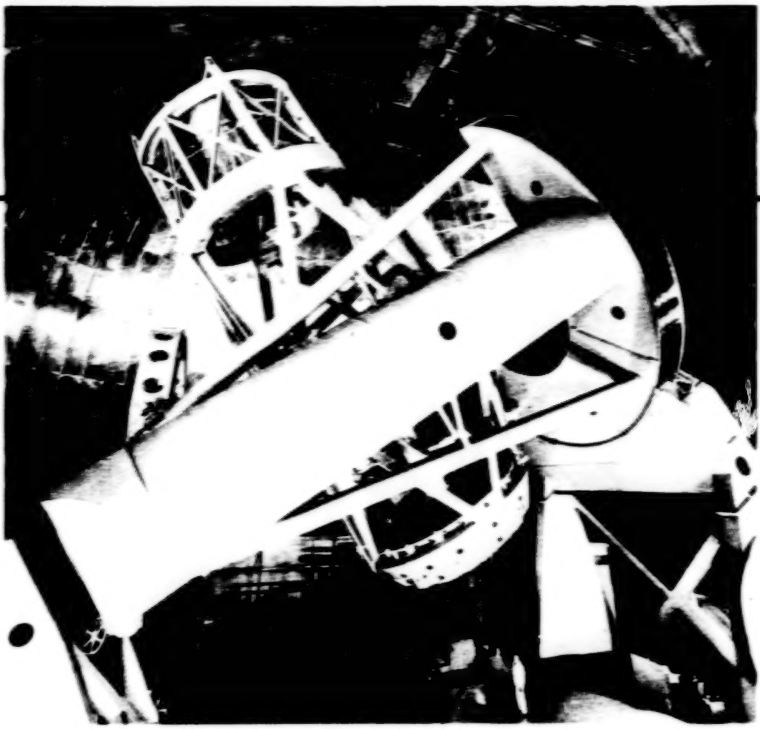
Several months after launch, when all checkout and verification exercises are completed, NASA officially hands over science planning responsibility for the Hubble Space Telescope to the Space Telescope Science Institute in Baltimore, Maryland. The Institute is responsible for the scientific use of the observatory, which will continue to be operated by the Goddard Space Flight Center. This dual control of the telescope's operation is a new arrangement that reflects some of the basic differences in the ways astronomers use observatories on the ground and in space.

The Hubble Space Telescope is not the first telescope in space; a number of smaller instruments have flown since the 1960's. However, it is the first large orbital observatory to be accessible to the worldwide astronomical community and the first such telescope to be considered "permanent." Like Mount Palomar or other world-class observatories on the ground, the Space Telescope will host a changing program of investigations and guest observers while it is in service. What is it like to be an astronomer using the Hubble Space Telescope?

To work in some of the best observatories on Earth, an astronomer may fly halfway around the world and then travel many miles overland to reach a remote mountaintop for a few nights of observation. Normally, he or she books time at the observatory several months in advance, arrives on the scheduled date and takes up residence there, hopes for several nights of good visibility, and, if the weather isn't cloudy, proceeds to observe whatever targets are critical to his or her research. Usually no one else is scheduled to use the facility at the same time, so the astronomer works without interruption. The observatory staff assist in configuring the equipment, pointing the telescope, and supporting the guest observer's plan. The astronomer and observatory technicians may sit side

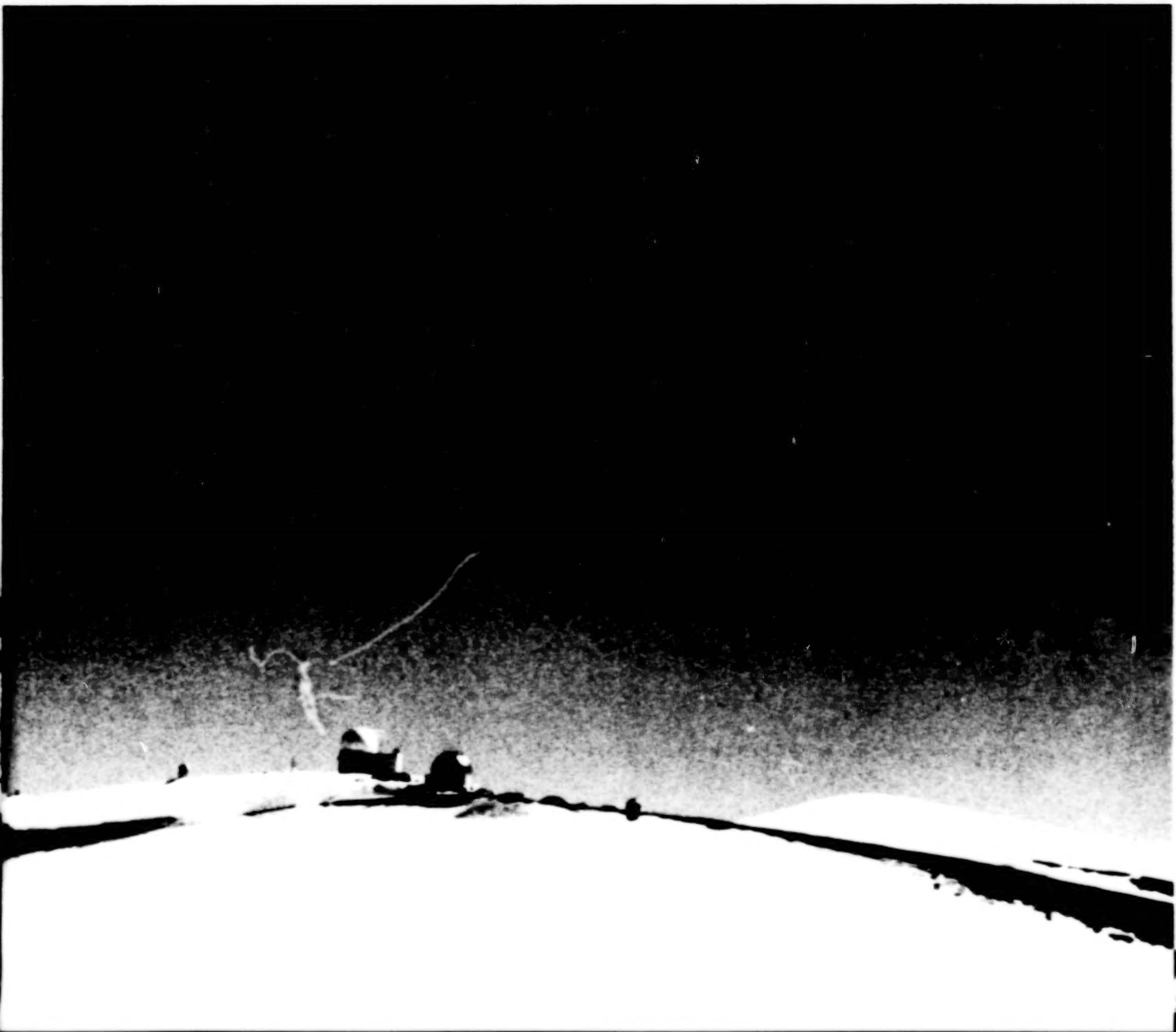


by side in the control room, choosing targets and adjusting the instruments through the night in response to observing conditions. The telescope is essentially an extension of the observer's senses, responding immediately to the astronomer's desire to linger on a particular target or look elsewhere. When astronomers go to bed at dawn, their work has only begun. The harvest of data from one night's observations may take months, even years, to analyze and understand.



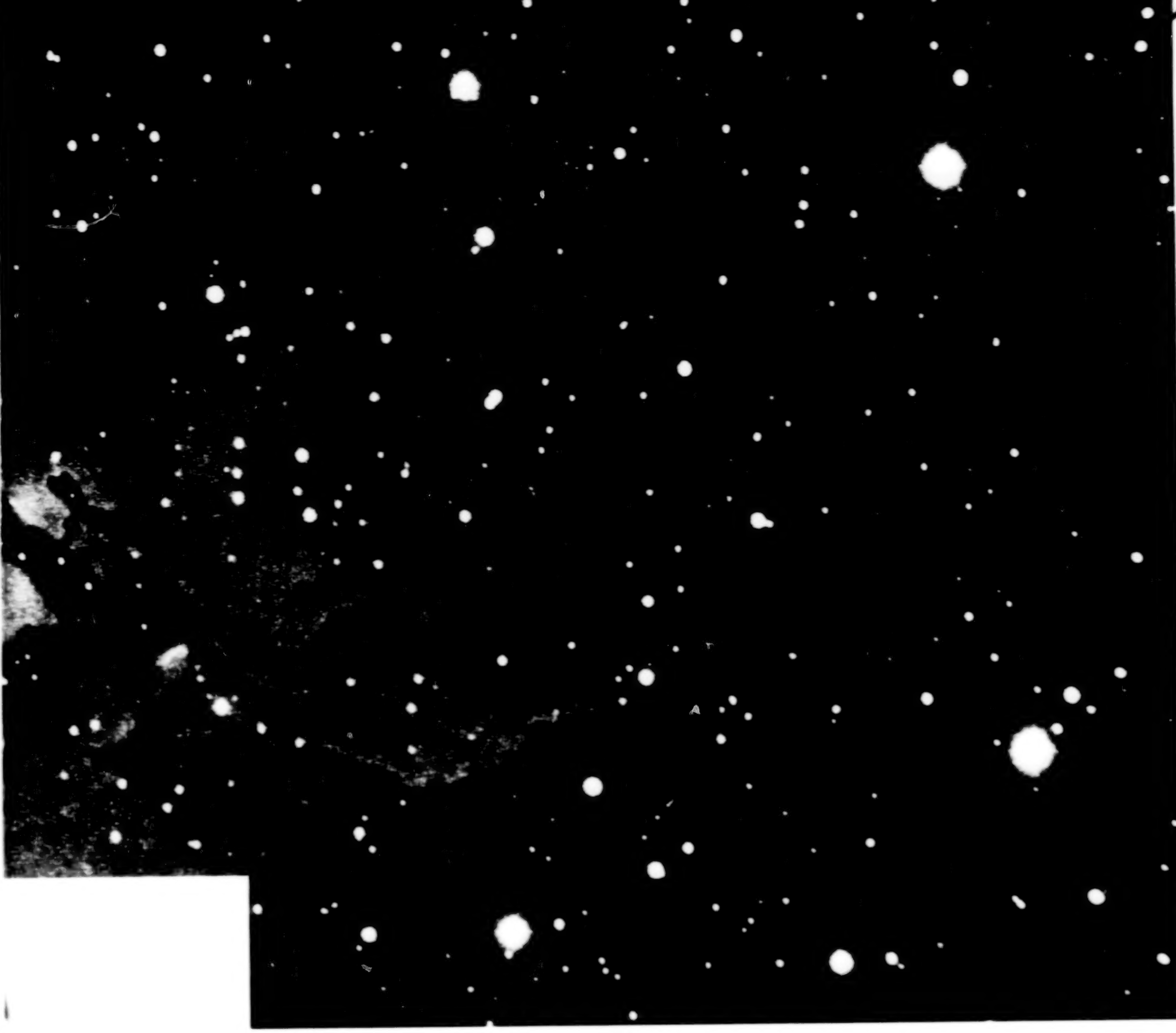
In observatories on the ground, astronomers work in a control room a few steps away from the telescope; however, the Hubble Space Telescope is a remotely controlled observatory.

Mountaintop observatories at Mauna Kea



Gaseous Nebula in Serpens

Right: A console is available for astronomers who wish to be present when their programmed observations occur. Some direct commanding is possible to control instrument settings and final positioning of the astronomical target in the field of view.



Observing with the Hubble Space Telescope

Likewise, if an astronomer's program requires a long observation, perhaps three hours on a target, the observation may be interrupted as the view from the orbiting telescope is blocked by the Earth or as some other activity takes precedence. Although the telescope operates around the clock, not all the time is spent in observing. Each orbit lasts about 90 minutes, with time allocated both for housekeeping functions and for observations. "Housekeeping" includes turning the telescope to acquire a new target or avoid the sun or moon, switching communications antennas and data transmission modes, receiving command loads and downlinking data, calibrating, and similar activities.

When the Science Institute completes its master observing plan, the schedule is forwarded to Goddard's Space Telescope Operations Control Center, where the science and housekeeping plans are merged into a detailed operations schedule. Each event is translated into a series of commands to be sent to the onboard computers. Computer loads are transmitted ("uplinked") several times a day to keep the telescope operating efficiently.

Normally, two of the scientific instruments will be used simultaneously to observe adjacent target regions of the sky. For example, while a spectrograph is focused on a chosen star or nebula, one of the cameras will be photographing a sky region offset slightly from the main viewing target. During observations, at least two of the three Fine Guidance Sensors will be operating, each tracking a separate guide star to keep the telescope pointed steadily at the right target.

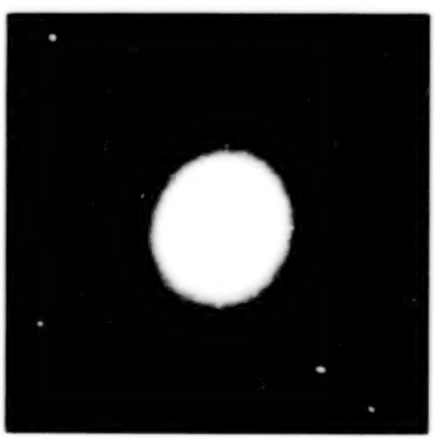
If an astronomer desires to be present during his or her observation, there is a console at the Science Institute and another in the Control Center, where monitors display images or other data as the observation occurs. Some limited real-time commanding for target acquisition or filter changing is performed at these stations, if the observation program has been set up to allow it, but spontaneous control is not possible. For some investigations, the observer may make fine adjustments to the telescope's pointing, using a light pen and cursor to center within an aperture a small target in a wider field. Whether or not the guest observer is present at the Institute, a staff astronomer and console operator are on duty at all times to monitor the observations. This is where real

The fields of view of the Fine Guidance Sensors form three "pickles," here superimposed on the Horsehead Nebula in Orion. To acquire an object for observation, the telescope must first locate appropriate guide stars with two of the three Fine Guidance Sensors. Candidate guide stars are shown as yellow crosses. The guide star catalog includes almost 19 million objects.

(Space Telescope Science Institute)

M81 galaxy in Ursa Major

(Kitt Peak National Observatory)

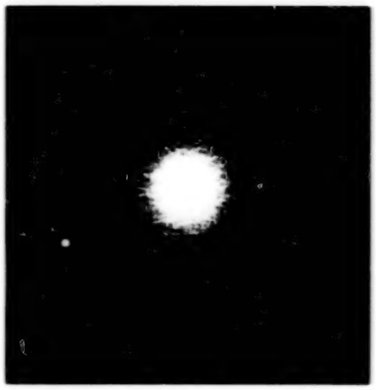


Giant elliptical galaxy M87 in Virgo

(Kitt Peak National Observatory)

excitement is felt as astronomers have a first look at what the telescope sees. The initial images and data are soon processed and refined by sophisticated computer programs on the ground.

In a much larger room at the Space Telescope Operations Control Center, 30 miles away, consoles are manned around the clock as operators stay in constant contact with the observatory, sending up commands, monitoring status, and receiving downlinked data. This is the nerve center. Behind the scenes at the Goddard and Marshall Space Flight Centers and at the industry sites where the telescope and its parts were developed, support teams stay on call to respond to any operational problems that may occur.



Globular star cluster in Pegasus, M15
(Kitt Peak National Observatory)

Engineering and scientific data from the observatory, as well as uplinked operational commands, are transmitted through the Tracking and Data Relay Satellite System (TDRSS) and its companion ground station at White Sands, New Mexico. Up to 24 hours of commands can be stored in the onboard computers. Data can be broadcast from the telescope to ground stations immediately or stored on tape and downlinked later.

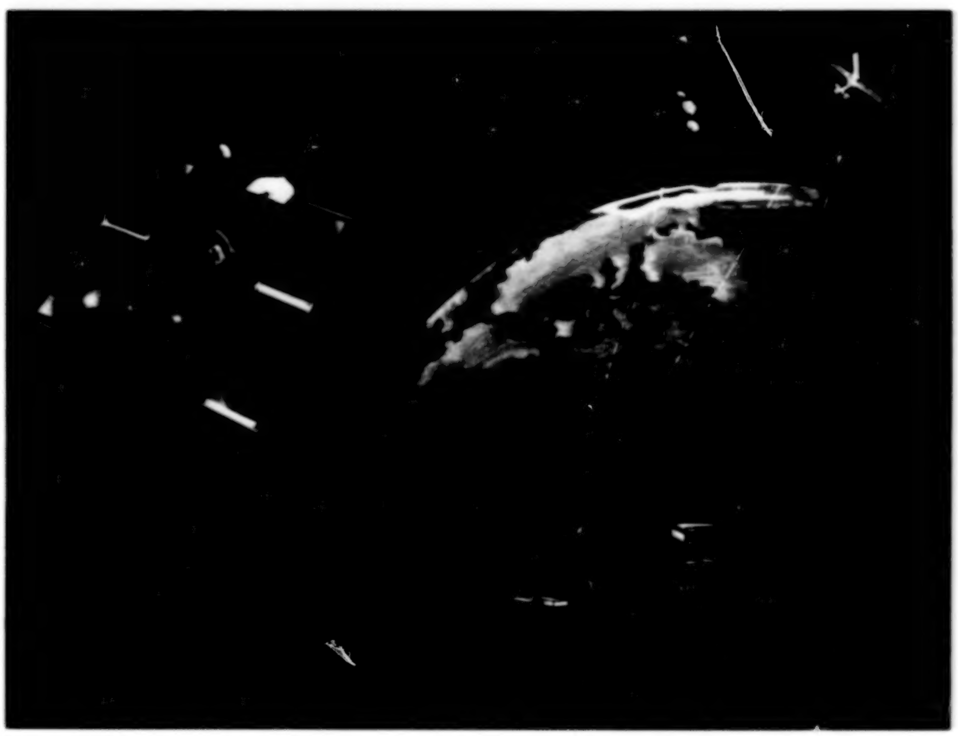
The observer on the ground can examine "raw" images and other data within a few minutes for quick-look analysis. Within 24 hours, Goddard formats the data for delivery to the Institute. The Science Institute is responsible for data processing; it calibrates, edits, distributes, and maintains data for the scientific community. The guest observer may analyze the data with software provided by the Institute or with his or her own programs, and the data may be analyzed at the Institute or at the observer's home institution. Eventually, observers around the world will be networked to the Institute, enabling them to have keyboard access to the data archives there.

Competition is keen for observatory privileges on the ground and in space, there being far more astronomers than large telescopes. The line to use the Hubble Space Telescope is already long, and for every one observer whose proposal is accepted there may be ten others waiting.

Most modern observatories are cooperatively used as national and international research centers. The Hubble Space Telescope will be operated in this tradition, as a resource for astronomers worldwide. Some observing time is allocated for amateur astronomers, as well. Data will be maintained in the Institute's archives and, when the primary investigators' research is completed, made available to all astronomers, not only those whose observations are accepted but also those who are waiting.

The perplexing problems in astronomy today cannot be resolved by a single instrument, a lone observer, or even one observatory. The new breakthroughs in theory and understanding are likely to come as a result of complementary investigations, involving several different instruments, observers, and observatories on the ground and in space. The Hubble Space Telescope program is organized to encourage collaboration and discovery.

M33 galaxy in Triangulum
(Kitt Peak National Observatory)



Data from the Hubble Space Telescope will be relayed by satellite and ground stations to the Goddard Space Flight Center for processing and then to the Space Telescope Science Institute in Baltimore, where the archives will be maintained. (NASA)

Servicing in Space

Two astronauts are absorbed in a task they have rehearsed for months: servicing the Hubble Space Telescope. Like members of a surgical team, each anticipates the action of the other and offers the proper tool or equipment as it is needed. They work quickly and with the confidence that comes from practice.

The Hubble Space Telescope rises like a tower from its repair platform in the Shuttle. The observatory is temporarily closed down, its solar arrays and antennas retracted and the aperture door closed. The immediate purpose of this servicing mission is to replace several batteries and sensor units that are reaching the end of their limited lifetimes.

Like an observatory on Earth, the Hubble Space Telescope can be repaired. As equipment wears out or becomes obsolete, it will be replaced. Already another observatory, the Solar Maximum mission, has been successfully repaired in space to extend its operation for several more years. The ability to service observatories in orbit is an important new way to extend their useful lifetimes. Servicing in space protects our substantial investment in technology to answer the highest priority questions in modern astronomy.

Routine service calls at the Hubble Space Telescope are scheduled at approximately three year intervals to replace batteries and other limited life items. These items, called Orbital Replacement Units, include components in the guidance and control systems and in the command and data handling system, a computer, solar arrays and the scientific instruments. Altogether, some 70 items in the Hubble Space Telescope can be replaced in orbit. The particular set of replaceable items varies

Astronauts test *servicing procedures with flight hardware on the ground to be certain that tools, fasteners, and other equipment fit and operate properly for servicing in orbit.* **More than 80 tools**, *including common screwdrivers and wrenches, are available.*

Like an observatory on Earth, the Hubble Space Telescope can be repaired. As equipment wears out or becomes obsolete, it will be replaced.

from mission to mission, depending on the condition of the observatory.

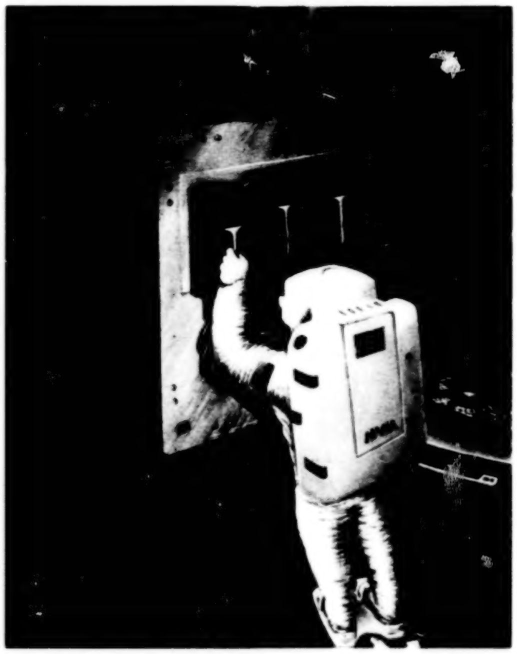
A repair mission begins with detailed planning and training on the ground, followed by a rendezvous in space. The Shuttle crew maneuvers to the telescope, captures it using the robot arm, brings the telescope aboard, and attaches it to a maintenance platform in the payload bay. There the telescope remains for several days while astronauts inspect it and exchange equipment.

The replacement units are readily accessible behind doors in the telescope shroud. Ranging in size from a shoebox to a telephone booth, most of the items can be removed or installed with the aid of wrenches and screwdrivers. Other crew aids include portable lights and foot restraints, small platforms that give the astronaut a stable foot-hold for the business of disconnecting electrical cables, disengaging latches and bolts, and replacing various pieces of equipment.

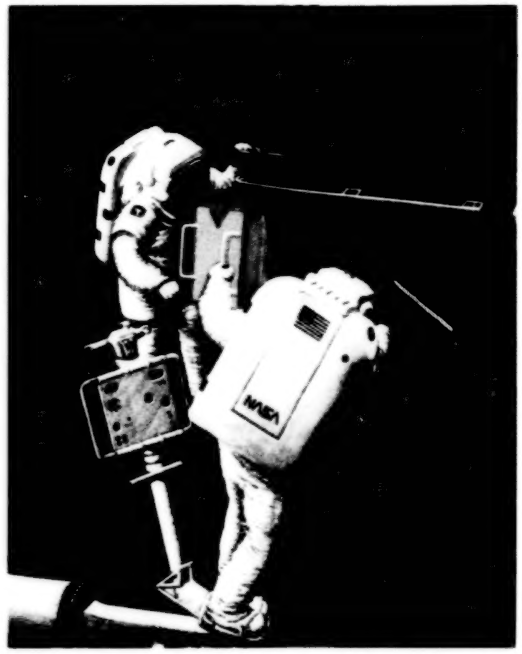
While attached to the maintenance platform, the repaired telescope undergoes status monitoring and checkout exercises, controlled by commands from the ground. If an orbit boost is necessary, the crew takes the Shuttle to a higher altitude for redeployment. Once again, the robot arm is used to lift and guide the telescope out of the payload bay. The solar arrays and antennas are extended again, the power is turned back on, and the telescope is released to resume operations.

If any problems arise during the redeployment, the Shuttle crew can retrieve the telescope and manually override a faulty mechanism. If the problem cannot be solved, the Hubble Space Telescope may be brought home. If all occurs according to plan, the telescope will remain in orbit doing its work until the next scheduled servicing mission.

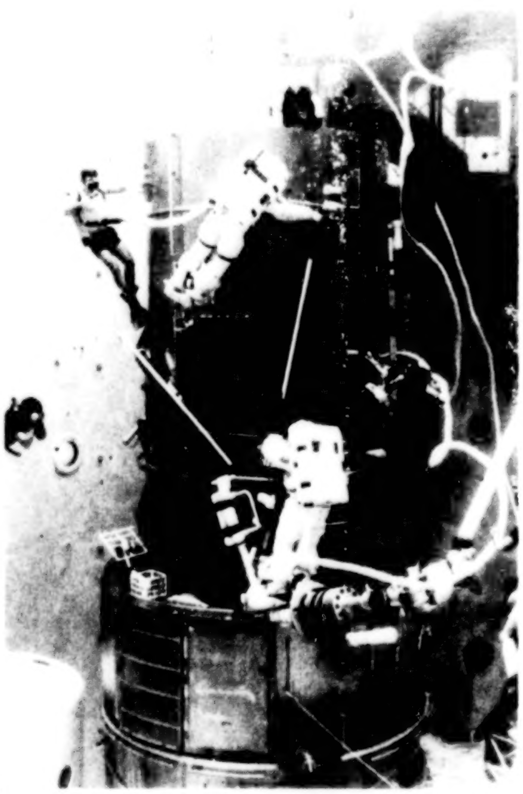
The Hubble Space Telescope is the first observatory designed for extensive maintenance and refurbishment in orbit. A long-lived mission is scientifically necessary for both discovery and detailed follow-up study.



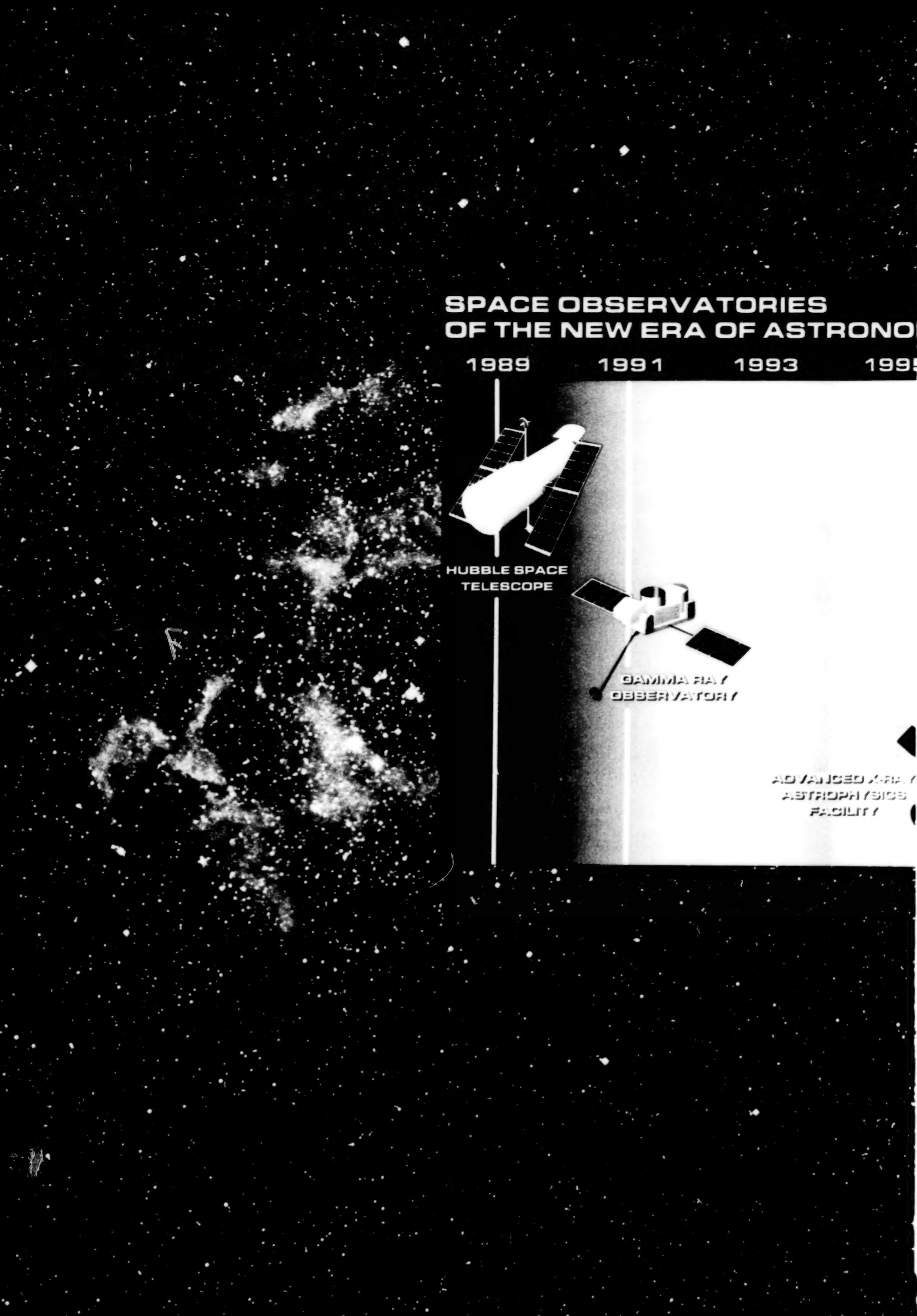
Many parts of the Hubble Space Telescope, such as the batteries, are designed to be removed and replaced.



Large units, such as the Fine Guidance Sensors and scientific instruments, also can be removed for servicing or replacement.

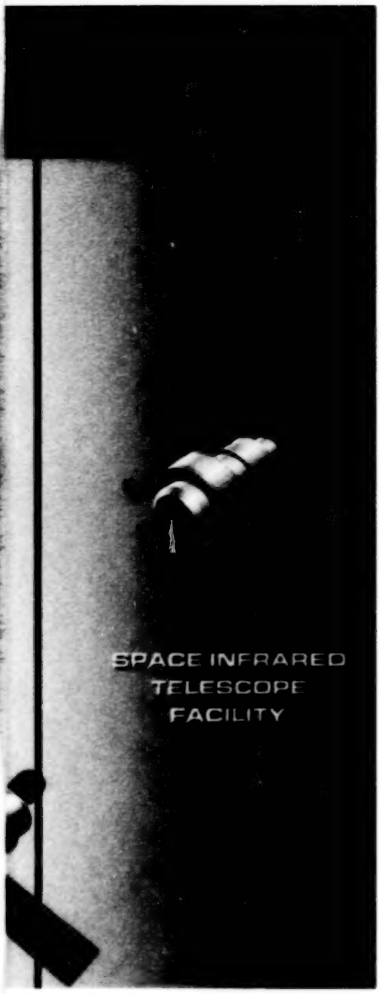


Servicing procedures are rehearsed underwater to simulate the weightless environment of space.


SPACE OBSERVATORIES
OF THE NEW ERA OF ASTRONO
1989
1991
1993
199
HUBBLE SPACE
TELESCOPE
GAMMA RAY
OBSERVATORY
ADVANCED X-RAY
ASTROPHYSICS
FACILITY

Opportunities for Discovery

Curiosity and technology: these are the prerequisites for modern astronomy and astrophysics. We question the cosmos, but most of the answers lie beyond the range of our observational tools. Many discoveries await the development of new technology for more precise measurements.



The Hubble Space Telescope is the first in a new family of Great Observatories designed to explore the universe across the electromagnetic spectrum. (NASA)

In just the past 40 years, the pace of discovery has dramatically accelerated as astronomers have taken advantage of rapid developments in technology. As a result, we now know that the universe contains not only the familiar planets, stars, and galaxies observed for centuries but also a rich variety of objects discovered quite recently. Quasars, pulsars, radio galaxies, X-ray stars and galaxies, infrared stars and galaxies, and gamma ray bursts have been identified in our lifetimes with technology that was not previously available. Some anticipated objects, such as black holes, have not been observed directly; their discovery requires techniques not yet in use today. Other objects not yet imagined await revelation by new instruments.

The Hubble Space Telescope is an instrument for discovery and prolonged study. Despite decades, even centuries, of curiosity, only now has the technology become available to build such a sensitive observatory and put it above the atmosphere. Advances in mirror, detector, materials, and space transportation technologies together make the Hubble Space Telescope possible in our lifetime. We will witness the new astronomy.

In the past 15 to 20 years while the Hubble Space Telescope was being designed and developed, progress in technology has marched on. Already, new detectors are becoming available, and the program includes development of "second generation" scientific instruments. After 5 to 6 years in orbit with its present instrument complement, the observatory may be refurbished in space. Some of the scientific instruments may be removed and replaced with new state-of-the-art detectors to extend our range of observation again. Just as the 40-year-old telescopes at Mount Palomar remain premier observatories through periodic upgrading with new technology, so the performance of the Hubble Space Telescope will keep pace with technological advances.

The Hubble Space Telescope is a key element in a broad campaign to observe the universe across the electromagnetic spectrum. This observatory will not be used in isolation but will be complemented by other telescopes sensitive to different wavelength bands. All matter radiates energy at different wavelengths, depending on the temperature of the matter. A telescope is, in a way, a remote thermometer detecting radiation within a specified wavelength (temperature) range. Because the spectrum from radio waves to gamma rays is so broad, no single telescope can detect all types of radiation or all objects.

Thus, NASA's strategy for astrophysics research is to launch a family of telescopes, the "Great Observatories," each tuned to a different channel of the spectrum. The Hubble Space Telescope is the flagship, to be followed by the Gamma Ray Observatory, and later the Advanced X-ray Astrophysics Facility and the Space Infrared Telescope Facility. These large observatories in space will operate for the next few decades. Together, they will give us a comprehensive look at the universe in all its guises.

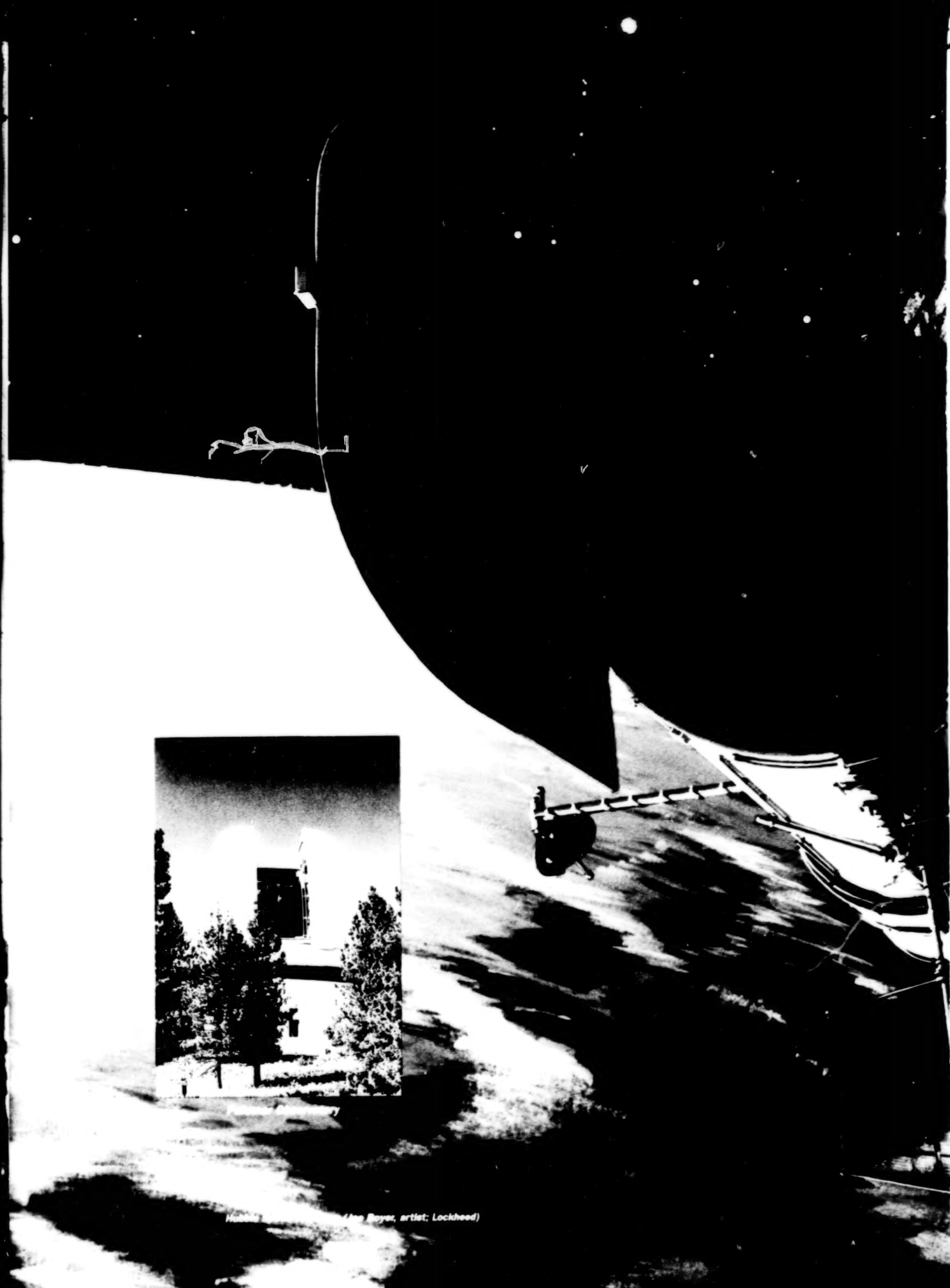
What we now know, though exciting, is probably less interesting than what we are about to learn. Where is technology leading astronomy? What new questions may be asked in the next generation? We can hardly guess today, but they will be guided by the Hubble Space Telescope, which will surely introduce us to objects and phenomena that we have not yet imagined. The really intriguing questions are the ones we don't even know to ask.

There is no doubt that our knowledge of the universe is going to change, perhaps as dramatically as it did when Galileo's telescopes confirmed Copernican theory that the Earth was not, after all, the center of the cosmos and that the Milky Way contained far more stars than anyone had ever suspected. The repercussions of these discoveries were felt throughout western civilization, not only in science but also in art and literature, philosophy and theology. We may enter the 21st century with radically altered perceptions of the universe, its origin, extent, contents, fate, and our place in it.

We are intrepid explorers, observing the distant stars and galaxies because our technology will not yet take us there. Until we can roam freely through the universe, we continue to explore it by capturing its light. Through the Hubble Space Telescope, many of those specks of light will become discernible objects—stars, galaxies, quasars, maybe planets and exotic things that we have never seen before.

This book is but a prelude; the next edition will present the universe newly revealed by the Hubble Space Telescope. We stargazers are eager to see!

Rosette Nebula in Monoceros (California Institute of Technology)



Hubble [illegible] (Joe Boyer, artist; Lockheed)

The Hubble Space Telescope:

Engineering Challenge

The problem of designing an observatory more capable than the best optical observatories on the ground but packaging it compactly enough to fit into the Space Shuttle and adapting it to operate while orbiting Earth every 90 minutes is not hypothetical. Engineers faced precisely that challenge in designing and fabricating the Hubble Space Telescope.

Imagine a building that contains all the mirrors, cameras, detectors, and computers for a high-precision observatory, plus all the supporting utilities (electrical power, temperature control, pointing mechanisms) and a communications center for telescope command and data flow. At Mount Palomar, such an observatory is a 12-story building, but the space available for the imaginary facility is about the size of a rai[illegible] car or an 18-wheeler truck, and its to[illegible] severely restricted to less than 13 tons. [illegible]her imagine that the building is in motion, moving so rapidly that night falls every hour and a half and lasts only 45 minutes. Despite its motion, however, the entire structure must be pointed toward a particular celestial object within a field of view as small as the full moon appears to be and held so still that very faint light from an object billions of light years away will enter the telescope and pass precisely through the center of a small hole to fall upon a detector. The least tremor will result in a loss of information and detail.

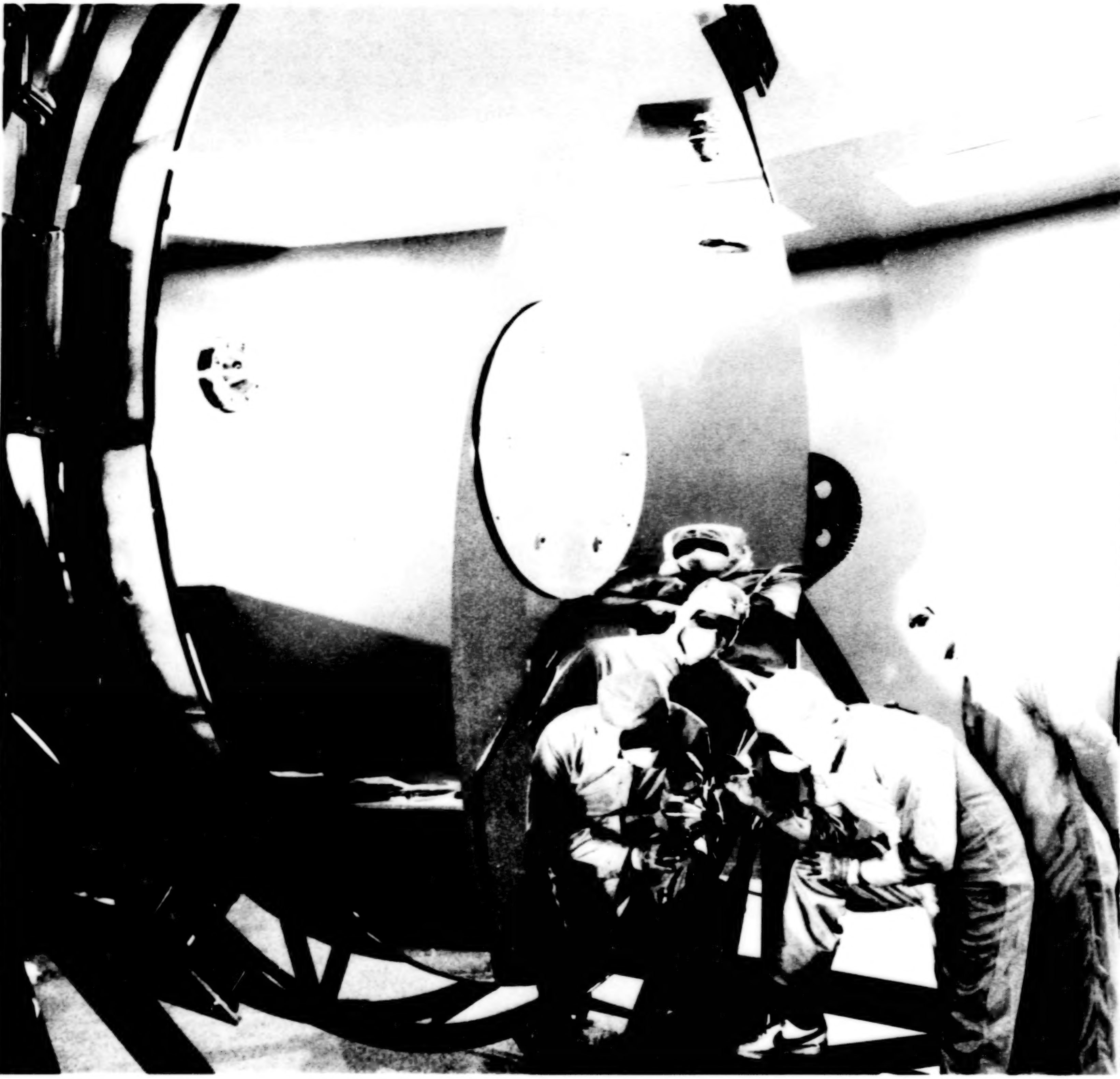
Designing and developing the systems for the most complex satellite ever placed in orbit presented extraordinary engineering demands. How was the Hubble Space Telescope designed, and how does it work? What was difficult about this particular telescope? The optical system, which collects and focuses light, and the pointing control system, which acquires the astronomical target and keeps the telescope "locked" on it: these were the primary technical challenges.

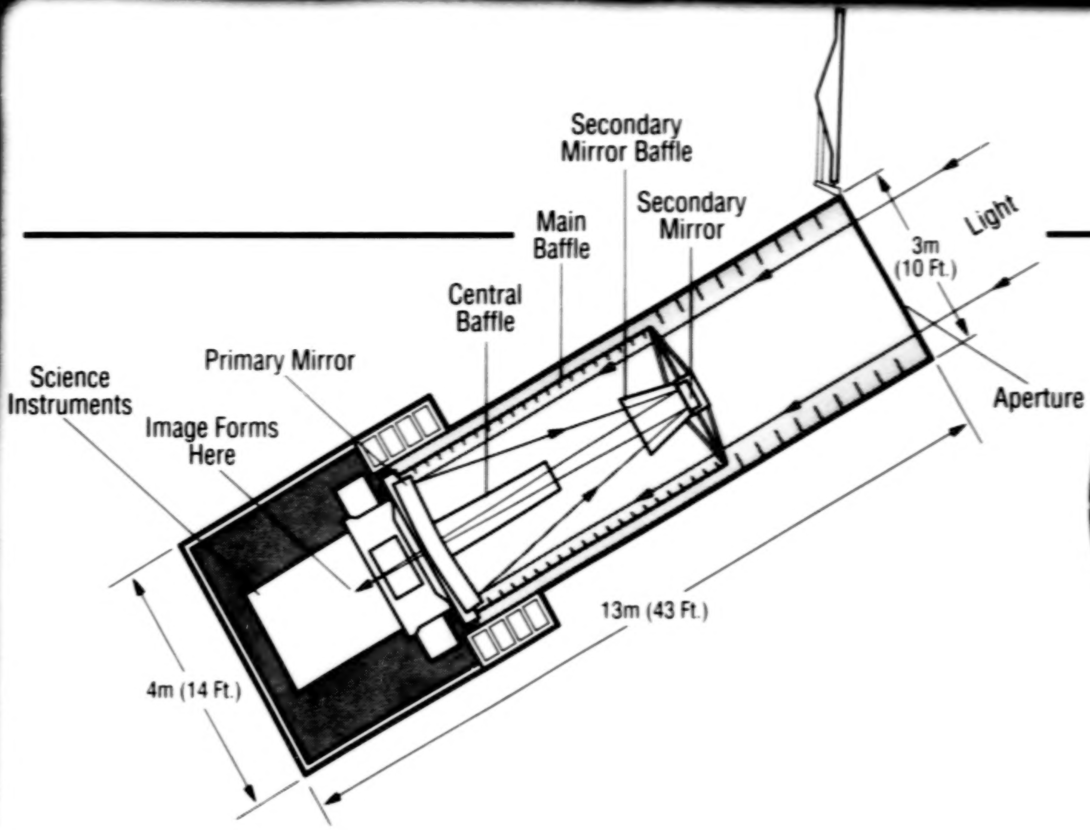
The primary mirror is coated with a layer of reflective aluminum (2.5 millionths of an inch), protected by a 1-millionth-inch layer of magnesium fluoride. It is the smoothest, most uniformly coated large mirror ever made. (Perkin Elmer Corp.)

In Focus

Telescopes collect light from a distant stellar source and concentrate the light onto a spot, preferably as small a spot as possible. As light travels away from its source, it spreads out in an expanding sphere, just as a balloon covers a larger and larger area as it is inflated. A telescope can be thought of as a "light bucket"; the primary mirror or lens is the collecting surface. The larger the mirror or lens, the more expensive and difficult it is to make.

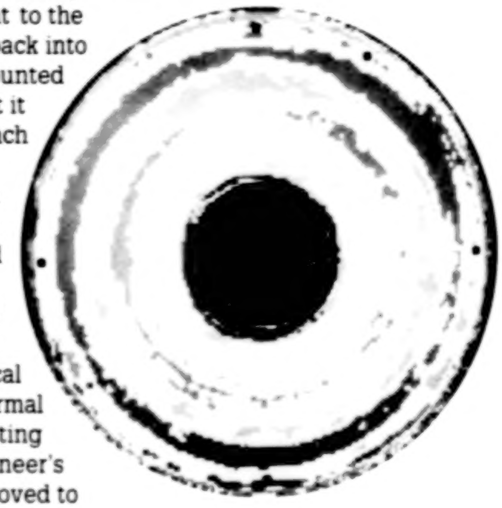
The aim of mirror design is to reflect all the collected light through the optical system and concentrate it onto a very small spot. For a single star, the spot is smaller than the period at the end of this sentence. The telescope also forms images of planets, galaxies, nebulae, and other extended sources that cover a larger area of the focal plane. The larger the mirror that collects light, the sharper the image of the distant object that





Layout of the Optical Telescope Assembly

The primary mirror surface must be virtually perfect. In these computerized maps of the mirror, the ideal surface is white. Meticulous polishing smoothed away high (blue) and low (red) variations in the surface. (NASA)



is the light source, if the mirror is very smooth. The mirror should be very smooth because any surface ripples or bumps degrade the image in the focal plane. The more bits of light (photons) that arrive at one spot, the brighter the image. The smaller the spot of concentrated light, the sharper the image and the fainter the source that can be detected.

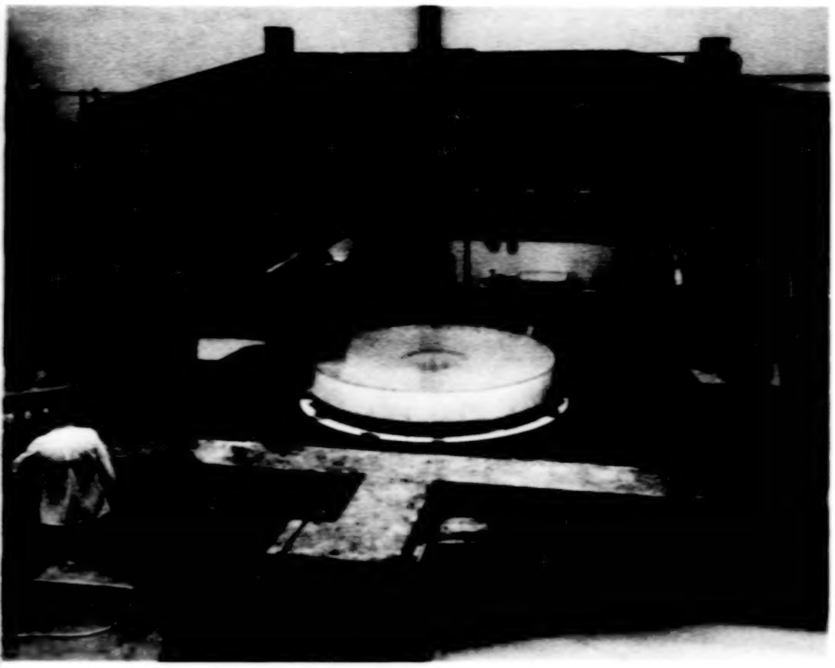
An optically perfect mirror concentrates light to the smallest spot possible, limited only by the wave nature of light itself and not by engineering imperfection. Early in the planning, NASA and the scientific community determined that the Space Telescope should be diffraction limited; that is, the deviation from perfection would be imposed by light, not by hardware. At the time, the technology did not exist to achieve this degree of optical perfection for a large mirror. The mirror foreseen for the Hubble Space Telescope was beyond the state of the art.

Besides being large and extremely smooth, the mirror had to be lightweight. The weight-to-orbit capability of the Space Shuttle or any other launch vehicle is limited, so every pound is critical. The 200-inch mirror at Mount Palomar weighs 14.5 tons; the 94.5-inch Hubble Space Telescope primary mirror had to weigh less than 1 ton. Engineers cleverly eliminated about 75% of the glass that would have been required in a solid mirror of this size by designing the Hubble mirror as a honeycomb structure. If it had been fabricated as a solid, the Hubble mirror would have weighed about 3 tons.

The Hubble mirror also had to be thermally stable, invulnerable to expansion and contraction as the telescope repeatedly passes from dayside heat to the frigid orbital night and back into sunlight. It had to be mounted rigidly enough to protect it from damage during launch vibrations but not so rigidly to warp or deform it. The telescope built on Earth had to be designed to operate in the much different environment of space. This combination of requirements for optical quality, light weight, thermal stability, and rigid mounting could have been an engineer's nightmare. Instead, it proved to be the stimulus for creative solutions.

Another requirement complicated the fabrication. The scientific community wanted a versatile large space telescope that operated not only with visible light but also with ultraviolet. Because each portion of the spectrum demands a different type of mirror coating, the design of the Hubble Space Telescope required engineering trade-offs and compromises. For example, aluminum is the best

The requirements for optical quality, light weight, thermal stability, and rigid mounting were a stimulus for creative solutions.



A special computer-controlled machine was designed for the grinding and polishing process. Final polishing was done by hand.
(Perkin-Elmer Corp.)

Development of the Hubble Space Telescope is a story of innovative engineering and technology.

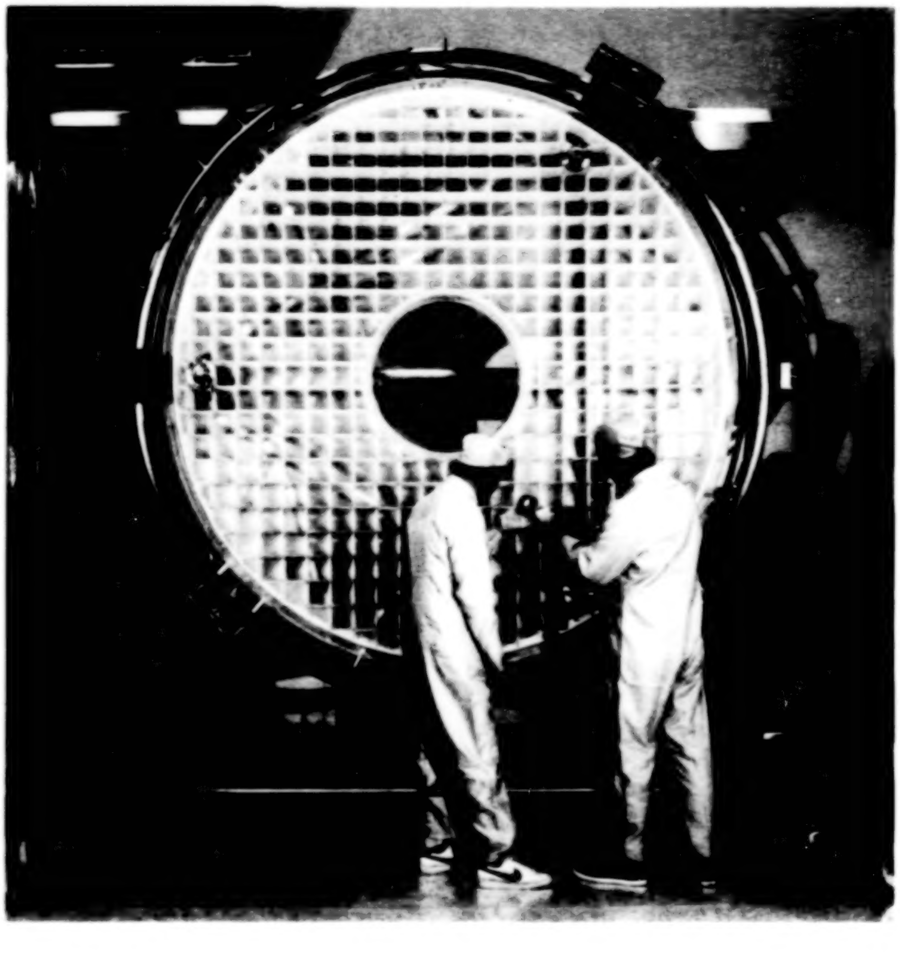
coating for visible light astronomy, reflecting up to 99.5% of the light, but it alone reflects almost no ultraviolet radiation. Aluminum oxidizes rapidly and must be protected by an overcoating in order to reflect ultraviolet. Furthermore, the overcoating must be just the right thickness to be transparent to both ultraviolet and visible light.

Given the different scientific objectives for the observatory, the solution was an aluminum layer with a magnesium fluoride overcoating to protect the mirror surface and optimize performance in the ultraviolet range. A slight overcoat of magnesium fluoride, much thinner than this sheet of paper, protects against oxidation and increases ultraviolet reflectivity to about 75%, but it decreases visible reflectivity to 85%. Though decreased from ideal, performance in the visible range is still quite satisfactory.

The coating process was particularly demanding because both coatings had to be extremely uniform for proper reflection, and they had to be applied in a high vacuum within a matter of seconds to avoid oxidation. Furthermore, the thinness of the magnesium fluoride overcoat had to be precisely controlled to achieve the desired ultraviolet reflectivity. A special chamber and equipment were prepared for the extremely delicate coating process, and technicians rehearsed the 10-second procedure for a year.

Development of the Hubble Space Telescope optical system advanced the state of the art in several disciplines. The mirror and optical system of the Hubble Space Telescope are the best that exist at their size. The 2.4 meter (94.5 inch) primary mirror is an efficient reflecting surface for visible light and is less effective but acceptable for ultraviolet. It is polished so smooth that the surface varies less than a millionth of an inch. The optical path is optimal for concentrating light from a single star at the focal plane.

Achieving this optical quality required new techniques of mirror fabrication, grinding and polishing, cleaning and coating, as well as highly precise analysis techniques to verify the uniformity and quality. To meet the weight, thermal, and mounting specifications, new materials and designs had to be devised, tested, and used. Each element is a story of innovative engineering and technology.



The inner honeycomb structure was visible before the mirror was coated.
(Perkin-Elmer Corp.)

While it awaited launch, the Hubble Space Telescope was kept meticulously clean. The mirror is extremely sensitive to contamination. Like a sunscreen that blocks ultraviolet rays, a coating of oil a few molecules thick on the magnesium fluoride would destroy its ultraviolet reflectivity. Grains of dust on the mirror would scatter light, producing a background haze that would limit the telescope's ability to detect faint objects. Components were "baked out" in a vacuum to get rid of vapors that would "outgas" and contaminate the optics in orbit.

Extraordinary precautions were taken to keep the telescope clean during assembly and checkout before flight. The chamber where it was kept was thousands of times cleaner than a typical laboratory. Temperature, humidity, and air flow were precisely controlled, and the air was thoroughly filtered. Technicians abided by a strict dress code and cleansing protocol to avoid bringing any contamination into the area. All materials, tools, cameras, even checklists used during the preflight assembly and testing had to be cleaner than clean.

Designing, developing, and assembling the optical system was a challenge faced on the ground, where people and machines could be used to solve the engineering problems as they arose. The telescope operates in space, however, far beyond the immediate reach of helping hands. The pointing control system was another complicated engineering assignment.

The Hubble Space Telescope was assembled and tested in a protected environment. Here the optical telescope and focal plane structure are visible before the outer shell was installed.

Still Light

Everyone who has tried photography knows the difficulty of holding a camera still and the disappointment of blurred images if the camera moves. The problem of jitter is magnified in telescopes, which require long exposures, sometimes hours, on the same object to produce images bright enough to detect. As the Earth turns, the star or galaxy being observed seems to move across the sky, so telescopes on the ground have to move slightly during an exposure to compensate for the Earth's rotation. A telescope must be able to lock onto a target of observation and hold the image still within the field of view, even as the instrument itself moves ever so smoothly to track the object.

Finding the astronomical target, locking onto it, and holding the image still is not an easy task on the ground, but the difficulty is compounded in an orbital telescope. On Earth, we use the bedrock of a mountaintop to steady a telescope, but what steadies a telescope in space? The Hubble Space Telescope is stabilized by a highly sophisticated dialogue between complex computer programs and control mechanisms.

The Hubble Space Telescope is the most precisely pointed machine ever devised for astronomy.

The Hubble Space Telescope is the most precisely pointed machine ever devised for astronomy. Its requirements for pointing stability and pointing accuracy are expressed in terms of multiple-zero decimals. The telescope must be able to maintain lock on a target for 24 hours without deviating more than 7/1000ths (0.007) of an arc second (2 millionths of a degree), about the width of a hair seen at a distance of a mile. Like the optical

system, the pointing control system stretched the state of the art to achieve this degree of accuracy.

The pointing control system comprises several different elements all working together to maneuver the telescope, guide it toward observation targets, and hold it steady. Maneuvers, or slews, are governed by reaction wheels, which generate control torques that turn the telescope, and rate gyros, which give the computer information about the telescope's orientation or attitude. The telescope can be maneuvered a quarter-turn (90 degrees) with the required accuracy and stability in about 18 minutes, moving slightly slower than the minute hand of a clock. The rate gyros report 40 times per second, and they are sensitive enough to detect position changes as small as .00025 arc second (7 hundred-millionths of a degree). Thus, they are also crucial in fine pointing during target acquisitions and observations.

During routine operations, three types of position indicators provide the information needed to point the telescope: the fixed head star trackers which are independent of the main telescope optics and can locate bright stars to a precision of about 1 arc minute (1/60th degree); the rate gyroscopes that provide precise angular measurements for short-term stability; and the fine guidance sensors which derive their signals from stars imaged near the edge of the telescope's field of view. The pointing control system uses four of six rate gyros and two fine guidance sensors to provide roll, pitch, and yaw information and keep the observatory locked on a celestial object.

Telescope motions are controlled by varying the speed of spinning reaction wheels. The reaction wheels receive commands from an onboard computer to generate torque, the force that produces rotation, and point the telescope to a given position with an accuracy of 0.01 arc second or less. The signal for these wheels is derived from a variety of sources—a coarse sun sensor, fixed head star trackers, gyroscopes, and interferometric star trackers—all processed by the flight computer. Four magnetic torquer bars on the exterior of the telescope, also controlled by computer, react against Earth's magnetic field to limit reaction wheel speed.

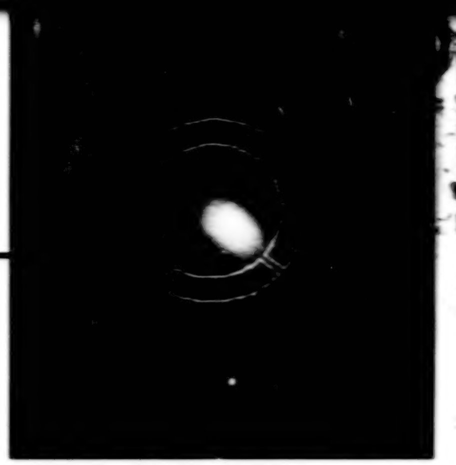
Target acquisition is governed primarily by the fine guidance sensors, which search for guide stars that will bring the target of observation into the instruments' field of view. Three fine guidance sensors have a horseshoe-shaped field of view at the perimeter of the focal plane. The master "reference book" for telescope pointing is the guide star catalog, a compendium of almost 19 million recognizable objects whose positions are known to about 1 arc second (3 ten-thousandths of a degree). The telescope uses guide stars rather than the actual observation targets for pointing. For any selected target of observation, the fine guidance sensors seek out guide stars that will bring the target precisely into the center of the selected detector's field of view. Each observation target is keyed to multiple guide stars, depending on the telescope's orientation, where it is in its orbit, and which detector is being used.

To acquire a target, two of the three fine guidance sensors must lock onto guide stars. The process of a typical target acquisition begins with a slew of the telescope to a predetermined position. The fixed head star trackers are used to determine the rough position of the telescope. Then the coordinates of a candidate guide star are fed into each of two fine guidance sensors. One sensor begins to seek the first guide star, searching in a spiral pattern until the proper star is found. Upon finding a star in the correct brightness range, it stops and the other sensor searches for another guide star. When the second star is found, the relative positions provide the final confirmation of position. If the position is not confirmed, the search resumes. The acquisition cycle typically takes about 20 minutes; in some cases, alternate methods may be used to reduce the acquisition time.

Once the guide stars are acquired, their light passes to a prism interferometer that provides a tracking signal. The basic stability reference is the set of rate gyros with positions that are updated every second by the fine guidance sensor signal.

The telescope locks onto the guide stars that bring the selected target into the field of view of the selected instrument. Each instrument has a method of automatically centering the science object in its aperture or sending down a real-time signal which will allow the observer to make a final decision on the exact pointing. In addition, the Wide Field/Planetary Camera can be used to make a quick image from which the position of the science target with respect to the guide stars can be determined, either in real time or later in the observing sequence. When the telescope locks on a target, the resulting stability enables high-resolution (fine detail) visible and near-ultraviolet images.

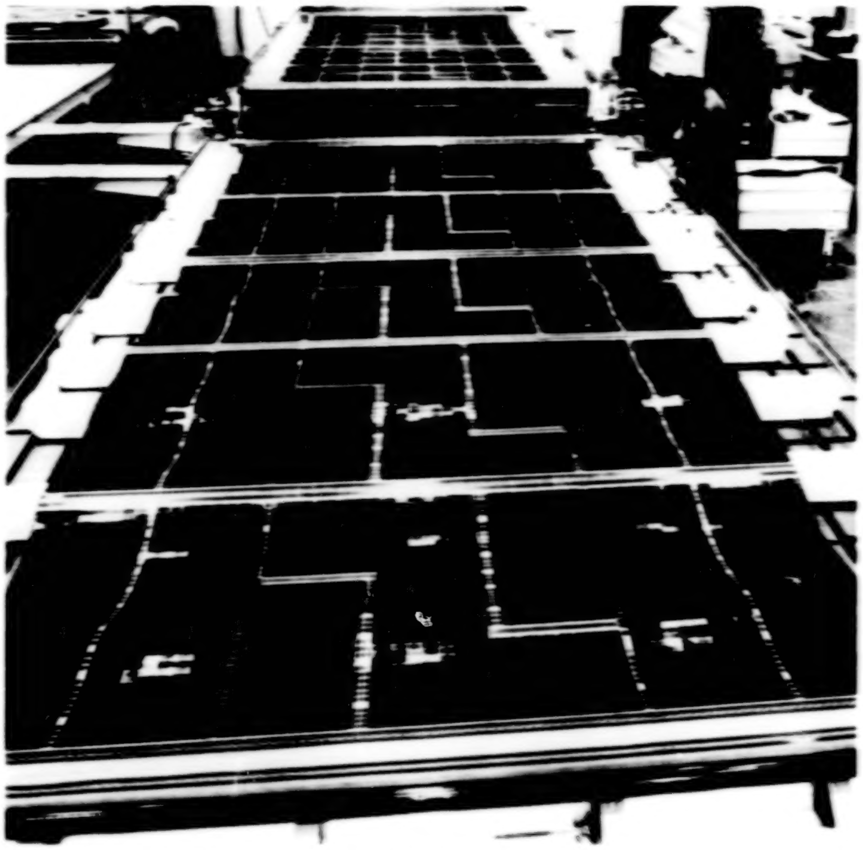
Three elements have to be held completely stable, with no jitter or disturbance whatsoever: the focal plane and both the primary and secondary mirrors. The biggest challenge for engineers and designers of the pointing and control system was to identify and control all line-of-sight disturbances that



Focal plane and Fine Guidance Sensor fields of view ("pickles") superimposed on the Andromeda Galaxy, M31

(Space Telescope Science Institute)

(NASA)



One of the two delicate wings of the solar array (NASA)

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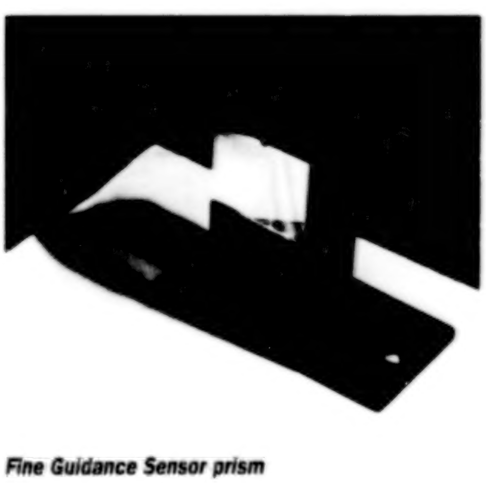


Fine Guidance Sensor prism (NASA)

might compromise the telescope's stringent requirements for pointing accuracy and stability. Some sources of error are in the equipment and can be controlled; for example, noise or vibrations from onboard electronics or thermal flexing can introduce random errors into the attitude and pointing signals. If the telescope jerks during a maneuver, the solar arrays will respond with a low-frequency wave that takes a long time to disappear. Gyroscopes "drift" and need frequent correction.

Over a longer time, a major temperature change brought about by telescope maneuvers may cause a long-term change in structural dimensions, which can have a significant degrading effect on precise observations. Therefore, all parts sensitive to temperature changes had to be made thermally stable; the truss structure, focal plane, and secondary mirror support were thus made of graphite-epoxy, a material that barely deforms as the temperature changes. Many elements also have thermostats and heaters to maintain active thermal control.

Other sources of error are environmental and must be compensated for, if not controlled. For example, the telescope is affected by a slight aerodynamic force and gravitational torque as it moves around Earth. Torques that act on the spacecraft must be nullified by the momentum management system to hold the telescope steady.

To attain the specified pointing stability and accuracy, several technological advances were required, particularly in the development of vibration-free equipment. The bearings in the reaction wheels, for example, had to be the best ever manufactured for perfect balance, and isolators were added in the reaction wheel assemblies to dampen any vibration. Likewise, the onboard tape recorders had to operate very smoothly and quietly.

The most demanding achievement in the pointin and control system was de and fabrication of the Fine Guidance Sensors, brand n systems capable of making extremely precise measure to a milliarcsecond. Makinc glass prisms for the interfe eters was an especially del and difficult effort. The twc halves of each prism are he together without glue, bolt or fasteners. They had to b smooth, so flat, and so clea they bonded by sheer mole attraction. When held in th polisher's hand, the glass c be deformed merely by boc heat. The prisms were alm impossible to make to the required perfection, and it repeated trials before the s prisms for flight (two per se were produced. The Fine Guidance Sensors will defir state of the art for the fores able future.

The onboard computer is brain for pointing and stabi the telescope. The compute contains the information rec to operate the telescope for several days without conta from the ground, although r mally a series of commands sent to the telescope every 24 hours. These instruction enable it to carry out a seq of observations automatica The computer executes com mands to individual compo in the various spacecraft su systems at the proper time accomplish the intended as nomical mission. Developm and verification of the softw code to perform all requirec functions were noteworthy achievements.

Development of The Hubble Space Telescope

The idea for the Hubble Space Telescope has been around for quite some time. This observatory may be the most deliberately and thoroughly planned astronomy program of the century.

The Hubble Space Telescope concept has its origins in the writings of Hermann Oberth in the 1920's and Lyman Spitzer in the 1940's. These scientists suggested that astronomy could benefit greatly from a telescope that viewed the universe from above Earth's obscuring atmosphere.

In the early 1960's, after NASA's formation in 1958, interest increased in astronomy as a scientific discipline to be pursued from space, and momentum grew for development of a large orbiting telescope. In 1962, NASA asked the Space Science Board of the National Academy of Sciences to study and recommend future astronomy payloads. At this time, NASA was already studying a concept for an Orbiting Astronomical Observatory, a 0.75-m (30-in) telescope for ultraviolet observations. Two studies were made, one at the State University of Iowa and the other later at Woods Hole, Massachusetts. The decision of the two work sessions was split, with some members of the group proposing a much larger telescope, (2.54 meters; 100 inches or more), and others dissenting on the basis that the smaller orbiting observatory would be temporarily satisfactory. Finally in 1965, a science board reviewed engineering studies and recommended that NASA develop a larger space telescope.

In the autumn of 1971, NASA began in earnest to do feasibility studies of the new telescope, then defined as a 3-m (10-ft) aperture telescope called the Large Space Telescope. The study results were favorable, and preliminary design was initiated in 1972. During this phase, the mirror size was reduced to 2.4 m (8 ft). The design study was continued until 1977, when Congress gave the approval to build and operate the observatory. By this time, the European Space Agency (ESA) had become a partner in the project, agreeing to provide the Faint Object Camera, the solar arrays, and staff support for telescope operations.

NASA selected two prime contractors to work on the Hubble Space Telescope project. Lockheed Missiles and Space Company in Sunnyvale, California, was responsible for designing, developing, and fabricating the support systems and assembling and testing all the major telescope components in the observatory. Perkin-Elmer Corporation in Danbury, Connecticut, was responsible for designing, developing, and fabricating the Optical Telescope Assembly. NASA also engaged contractors to build the scientific instruments.

NASA selected a group of scientists to participate in the design and early operational phase of the project. Their charter was to define the observing plan for the telescope, establish scientific priorities, and organize operations to obtain the best results from this new research facility. During the two decades of telescope design and development activity, the scientific community has been formulating and refining this observing plan through a well-organized process of study groups, proposals, and peer review. The program continues to mature as new information from other astronomy missions influences the inquiries and objectives to be pursued with the Hubble Space Telescope.

In late 1983, as the telescope neared completion, it was renamed in honor of the American astronomer Edwin P. Hubble. Launch was tentatively scheduled and postponed several times into the late 1980's with telescope development problems and delays in the Shuttle program. During the long and eager wait for launch, time was well spent in additional ground tests, crew and operations team training, and science planning.

A "constellation" of NASA centers, European Space Agency affiliates, universities, research laboratories, industrial contractors, and their vendors in the United States and Europe participated in the development of the Hubble Space Telescope.

The Hubble Space Telescope during pre-flight testing

Guided Tour

of the Hubble Space Telescope

The Hubble Space Telescope is just over 13 meters (43 feet) long and 4 meters (14 feet) in diameter, about the size of a bus or tanker truck. Upright, it is a five-story tower; carried inside the Space Shuttle for the trip to orbit, it fills the payload bay.

The Hubble Space Telescope is made up of three major elements: the Optical Telescope Assembly, the focal plane scientific instruments, and the Support Systems Module, which is divided into four sections, stacked together like canisters:

Aperture Door and Light Shield: protecting the scientific instruments from light of the sun, Earth, and moon and also from contamination

Forward Shell: enclosing the Optical Telescope Assembly mirrors

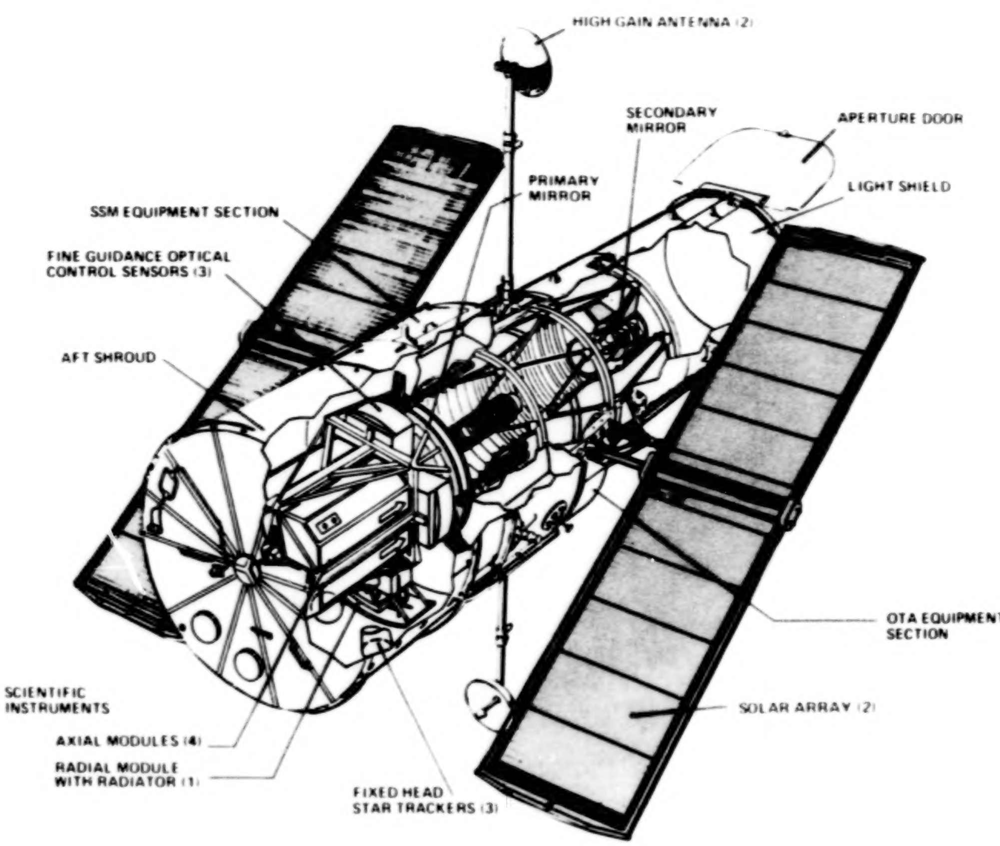
Equipment Section: girdling the telescope to supply power, communications, pointing and control, and other necessary resources

Aft Shroud: covering the five focal plane instruments and the three fine guidance sensors.

Solar energy arrays and communications antennas are attached to the exterior shell. Doors allow astronauts to remove instruments and components from the equipment bays. Handrails and sockets for portable foot restraints attached to the external surface aid the astronauts in performing maintenance and repair tasks.

Space Telescope Vital Statistics

Length:	*13.1 m (43.5 ft)*
Diameter:	*4.27 m (14.0 ft)*
Weight:	*11,000 kg (25,500 lb)*
Focal Ratio:	*f/24*
Primary Mirror	
Diameter:	*2.4 m (94.5 in)*
Weight:	*826 kg (1,825 lb)*
Reflecting Surface:	*Ultra-low expansion glass covered by aluminum with magnesium-fluoride coating*
Secondary Mirror	
Diameter:	*0.3 m (12 in)*
Weight:	*12.3 kg (27.4 lb)*
Reflecting Surface:	*Ultra-low expansion glass covered by aluminum with magnesium-fluoride coating*
Systems	
	Optical Telescope Assembly
	Support Systems Module
	Focal Plane Science Instruments
	Wide Field/Planetary Camera
	Faint Object Camera
	Faint Object Spectrograph
	Goddard High Resolution Spectrograph
	High Speed Photometer
	Fine Guidance Sensors (for astrometry)
Data Rate:	*Up to 1 mbps*



Hubble Space Telescope Configuration

The optical system operates on the same principle as reflecting telescopes invented in the 17th century.

Optical Telescope Assembly

The optical system operates on the same principle as reflecting telescopes invented in the 17th century by Isaac Newton, Guillaume Cassegrain, and James Gregory. Reflecting telescopes use mirrors to gather and concentrate light onto different types of detectors. The Hubble Space Telescope is a Ritchey-Chretien variation of the Cassegrain telescope configuration; that is, the two mirrors are exactly figured to eliminate the optical aberrations of ordinary Cassegrain telescopes.

The telescope design uses two hyperbolic mirrors, one concave and one convex, in an arrangement that economically packages a long focal length telescope into a shorter tube. The Hubble Space Telescope is free of coma, the long, comet-like blur that limits the field of view of some telescopes.

Baffles in front of the primary mirror and behind the secondary mirror prevent scattered light from outside the telescope from reaching the image plane.

To avoid warping, the mirrors are made of ultra-low expansion glass and kept at a nearly constant room temperature (21 °C / 70 °F). The reflecting surfaces are coated with a layer of pure aluminum about 3 millionths of an inch thick, protected with a 1 millionth-inch layer of magnesium fluoride for high reflectivity of ultraviolet wavelengths.

The primary mirror is 2.4 m (94.5 in) in diameter, and the secondary mirror is 0.3 m (12 in). The two mirrors are mounted 4.6 m (16 ft) apart on a lightweight but rigid structure, the metering truss, that keeps them perfectly aligned. A 60-cm (2-ft) diameter opening in the primary mirror allows light to converge in the focal plane, located some 1.5 m (4.9 ft) behind the mirror. The focal plane is about the size and shape of a dinner plate.

Focal Plane Scientific Instruments

The instrument complement consists of two cameras, two spectrographs, one photometer, and the Fine Guidance Sensors. The cameras record light and convert it to electric signals, which are transmitted to the ground where they are interpreted as photographs. The spectrographs separate ultraviolet and visible light into their component wavelengths and measure the intensity of the radiation in different wavelengths, yielding information on the chemical composition of objects in the universe. The photometer measures the intensity of incoming light; these brightness measurements allow calculations of size and shape, and of distance between celestial objects. The Fine Guidance Sensors precisely determine the position/location of celestial objects, yielding

information about their rates and directions of motion.

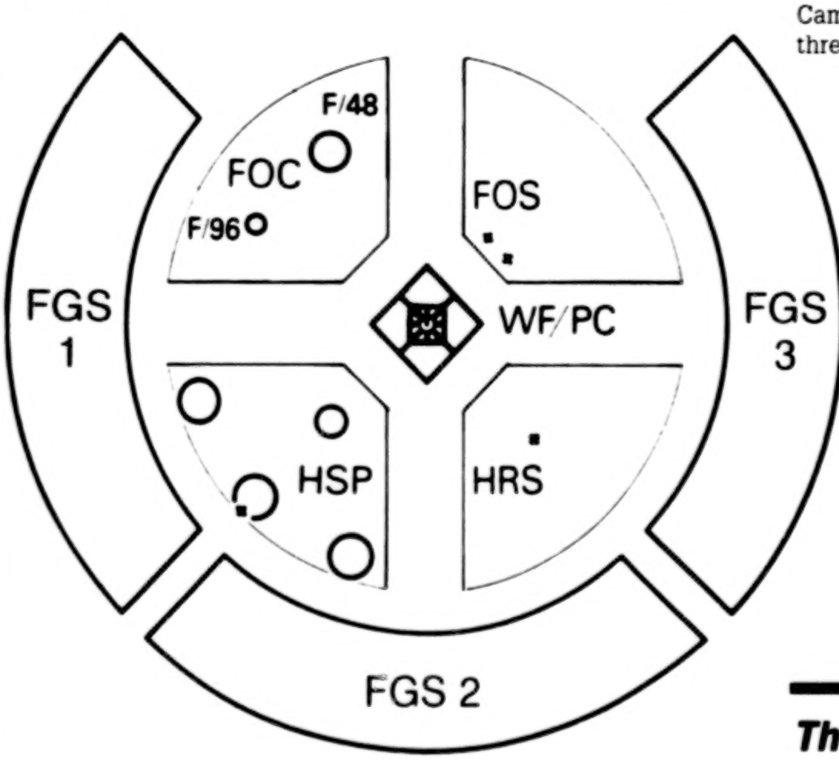
The scientific instruments are located behind the primary mirror, where they collect information by sampling the light brought to focus in the focal plane. There are four U.S. instruments—the Wide Field/Planetary Camera, the Faint Object Spectrograph, the Goddard High Resolution Spectrograph, and the High Speed Photometer—and one European instrument—the Faint Object Camera. The Fine Guidance Sensors used for pointing control also are used for astrometry to measure the positions of celestial objects. Each instrument is housed in a module that can be removed by astronauts for repair or replacement. Special latches keep the instruments properly aligned and allow quick release for easy removal.

The scientific instruments are in separate bays, allowing them to be operated and replaced independently of one another. Four are in bays that run parallel to the observatory's axis, the axial bays. These instruments are mounted with their long dimensions parallel to the optical axis of the telescope and their entrance apertures in the focal plane. The axial bays and instruments are about the size of telephone booths; they are accessible through large doors in the aft shroud.

The Wide Field/Planetary Camera and the three Fine Guidance Sensors are located in the radial bays in front of the axial bays. Oriented at right angles to the other instrument modules, the radial instruments can be pulled out like large drawers. Since the radial instruments are not directly in line with the optical axis of the telescope, light is deflected at right angles by small "pick off" mirrors into the Wide Field/Planetary Camera and the Fine Guidance Sensors.

The focal plane is divided into eight segments, one for each of the four axial instruments, one for the Wide Field/Planetary Camera, and one for each of the three Fine Guidance Sensors. This division was the most cost-effective way to provide access to the focal plane for more than one scientific instrument. For some observations, a centrally located axial instrument can be operated simultaneously with the radially located Wide Field/Planetary Camera.

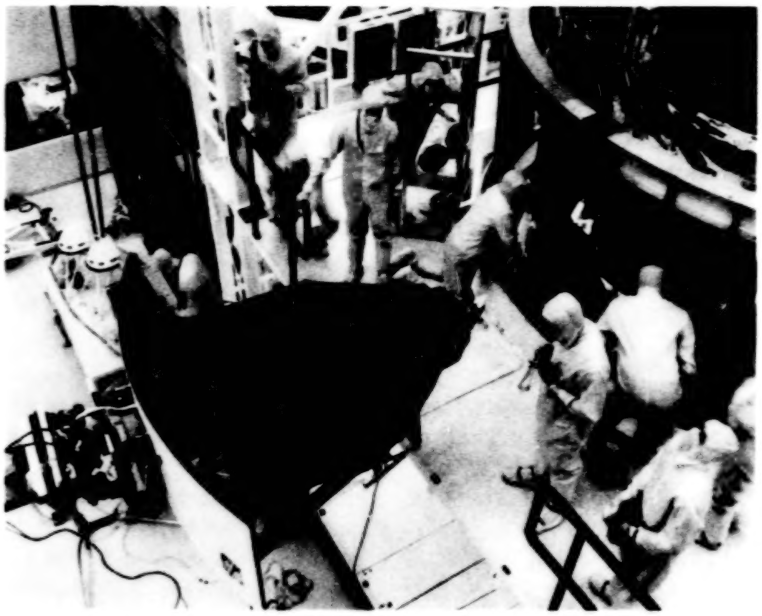
Each of the scientific instruments contains two or more advanced light detectors and supporting electronics. All but the High Resolution Spectrograph have dedicated microprocessors, and all but the High Speed Photometer have mechanisms to move optical components such as mirrors, filters, and diffraction gratings (devices that separate light into its component colors or wavelengths) into the optimum position for each observation.



Eight instruments share the focal plane, which is about the size and shape of a dinner plate.

The focal plane scientific instrument complement includes:

- ***Wide Field/Planetary Camera***
- ***Faint Object Camera***
- ***Faint Object Spectrograph***
- ***High Resolution Spectrograph***
- ***High-Speed Photometer***
- ***Fine Guidance Sensors***



Wide Field/Planetary Camera installation *(Lockheed)*

Wide Field/Planetary Camera
The Wide Field/Planetary Camera will observe larger sky areas and produce more data than the other instruments. This visible light camera operates in two modes: the planetary mode for exploring our own nearby solar system and the wide field mode for the farther reaches of the universe.

In the wide field mode, the camera can make images of swaths of the universe for mapping distant galaxies and quasars. In four exposures, for example, it can photograph a giant galaxy in the Virgo cluster at an estimated distance of 60 million light years. The camera's field of view will contain dozens or even hundreds of galaxies located at distances of billions of light years. In this mode, the image clarity will be about 10 times sharper than typical photographs made at Earth-bound observatories.

In the planetary mode, this camera can photograph in a single exposure the entire face of any planet in our solar system, except Mercury, which is too close to the sun. Images of the outer planets Uranus and Neptune will be much better than those produced by ground-based optical systems. Pictures of closer planets, such as Jupiter, will resemble images from the Voyager spacecraft that approached the planet. Unlike images from ground-based telescopes, which can be made only at night when skies are clear, these images will be possible on a routine basis; unlike Voyager images, which were snapshots frozen in time, the series of new images will reveal changes occurring over time, such as volcanic activity and atmospheric circulation.

The Wide Field/Planetary Camera has 50 filters to sort radiation into different spectral bands. A star of the 16th magnitude (about 10,000 times fainter than the faintest stars visible to the naked eye) can be photographed in just one-tenth of a second. In longer exposures of 50 minutes or more, the camera can record stars of the 28th and 29th magnitude, about 40 times fainter than the dimmest objects routinely photographed with large ground-based telescopes. (From the ground, 24th magnitude can be detected in overnight exposures; on rare occasions, detection of 26th magnitude is possible.)

The Wide Field/Planetary Camera will observe larger sky areas and produce more data than the other instruments.

This simulated Wide Field/Planetary Camera image of a random starfield shows stars as faint as 31st magnitude in a 10-minute exposure.
(Space Telescope Science Institute)

Faint Object Camera

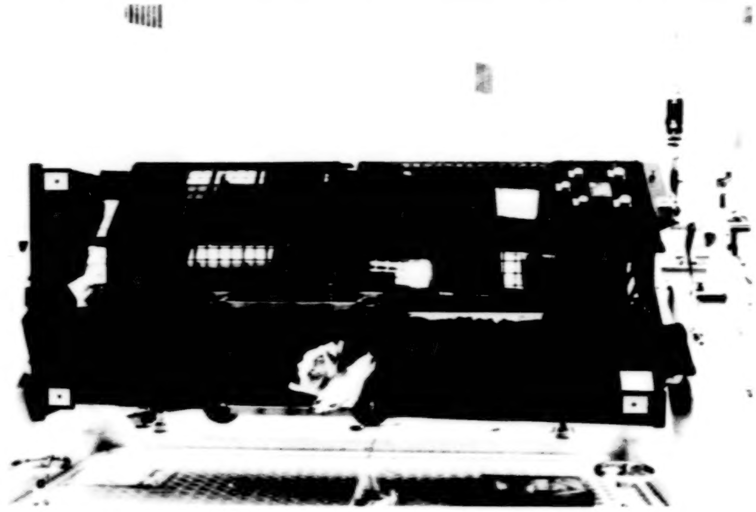
This instrument, built by the European Space Agency, obtains images of very faint objects, collecting information on objects at the greatest possible distances. It will detect stars as faint as the 28th magnitude and will easily pick out stars of the 24th magnitude, the limit of most large ground-based observatories. Many stars now considered dim will be readily seen.

An electronic image intensifier, capable of recording the arrival of individual photons, enhances feeble starlight and creates an image in the camera that is more than 100,000 times brighter than the image focused by the telescope mirror. Brighter wavelengths can be blocked by filters so that weaker ones can be recorded.

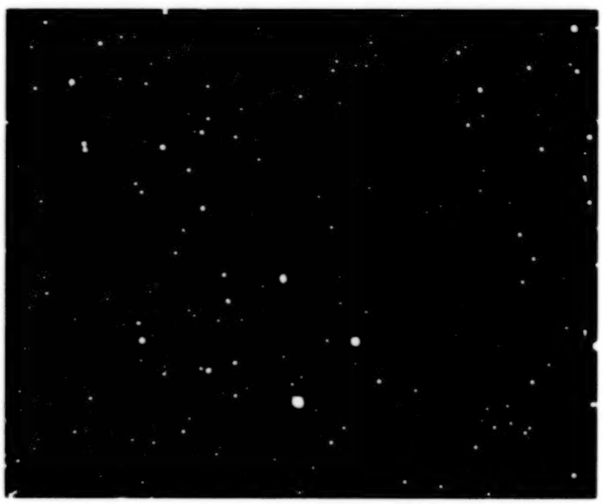
This camera is more sensitive in blue and ultraviolet light than the Wide Field/Planetary Camera, which is more sensitive to green and longer wavelengths. This instrument has sharper resolution, but the Wide Field/Planetary Camera covers larger areas. Astronomers can judge the merits of each camera and choose to use the one that best suits their needs.

The Faint Object Camera will be able to see stars in binary systems that are invisible from the ground because their light is so weak. Nebula observations can take years of tedious observing from the ground; however, this instrument will be able to detect individual stars embedded in the gaseous filaments of nebulae in a matter of months.

The uniquely high resolution of the Faint Object Camera will enable us to distinguish fine details around the nuclei of active and distant galaxies, to search for black holes in nearby galaxies, and to study the surroundings of such very distant objects as quasars. Sensitive images with high resolution in the ultraviolet will show regions in distant galaxies where hot young stars are currently forming after collisions between galaxies. Some of the remarkable jets coming from the nuclei of galaxies, observed by radio telescopes, will be imaged for the first time in visible and ultraviolet wavelengths.

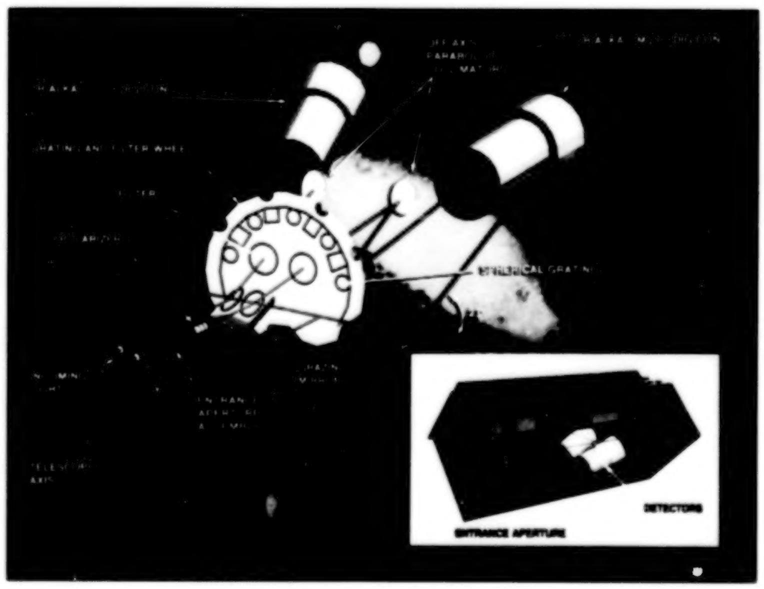


Faint Object Camera installation (Lockheed)



Veil Nebula (U.S. Naval Observatory)

The Faint Object Camera, built by the European Space Agency, will collect information on very faint objects at a greater distance than ever before possible.



Faint Object Spectrograph installation *(Lockheed)*

Faint Object Spectrograph

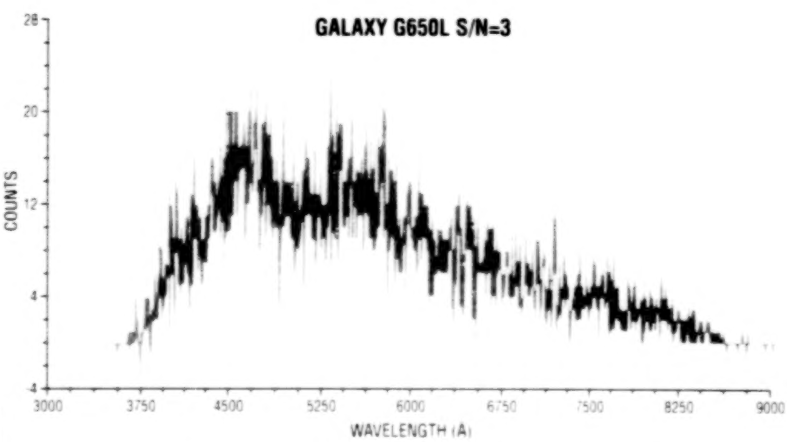
Light radiated from celestial objects is a mixture of wavelengths over a broad range of energy, indicating the presence of various chemical elements. The atoms of a given element emit or absorb light in a unique manner according to such physical conditions as temperature and pressure. By studying spectra, we can learn whether an object is hot or cold, dense or rarefied, and we can determine much about its chemical composition. Analysis also can reveal the object's distance from Earth and its velocity.

This instrument can produce spectra of extremely faint astronomical sources located so far away from Earth that the feeble light now collected yields only sparse information. As light from a star or other celestial object strikes the telescope's focal plane, the Faint Object Spectrograph uses a system of mirrors and gratings to separate the rays of light into wavelength categories. The light is spread out and recorded by a device that registers each photon. The product is a spectrogram that reveals the light's intensity and distribution over various wavelengths.

Two occulting devices can be used to block light at the center of an image, creating an artificial eclipse for studying faint objects (nebulae or stars) close to much brighter objects. Candidate targets for this technique are the dim shells of gas around giant stars and the fainter stars in a bright galaxy.

This instrument also allows astronomers to study the polarization of light emitted from objects. Polarization is the tendency of light waves to be oriented in a particular plane or direction under the influence of a magnetic field or passage through an interstellar dust cloud.

The Faint Object Spectrograph will produce spectra of extremely faint astronomical sources.



Simulated FOS spectra of an early-type galaxy
(Space Telescope Science Institute)

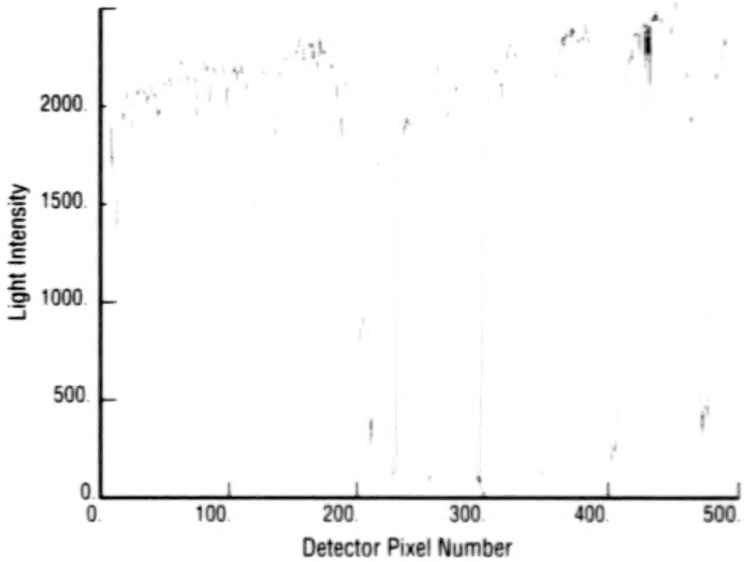
Goddard High Resolution Spectrograph

The Goddard High Resolution Spectrograph operates in a similar manner to the Faint Object Spectrograph, recording and classifying radiation from celestial sources, but it is more sensitive and has better resolving power to produce more detailed ultraviolet spectra. The High Resolution Spectrograph is blind to visible light so that it can sense faint ultraviolet emissions from bright visible stars. While the Faint Object Spectrograph captures the broader spectral picture, the High Resolution Spectrograph analyzes only ultraviolet radiation that never penetrates Earth's atmosphere.

High-resolution ultraviolet astronomy has been limited to bright targets. This instrument is able to detect objects 1,000 times dimmer than those previously observed by instruments in space. Because of the instrument's extremely fine resolution, individual stars will be distinctly visible in crowded fields. Binary stars whose traits merge together in optical observations will be resolved so that each star can be studied.

In the ultraviolet, astronomers expect to find detailed information about the chemical composition of hotter stars. This instrument will detect trace substances in interstellar space which are undetected by other means, as well as gases in comets, the atmospheres of planets, interstellar gas, and other rarefied media throughout the universe.

Goddard High Resolution Spectrograph installation
(Lockheed)



Spectrum obtained during laboratory testing of this instrument
(Ball Aerospace)

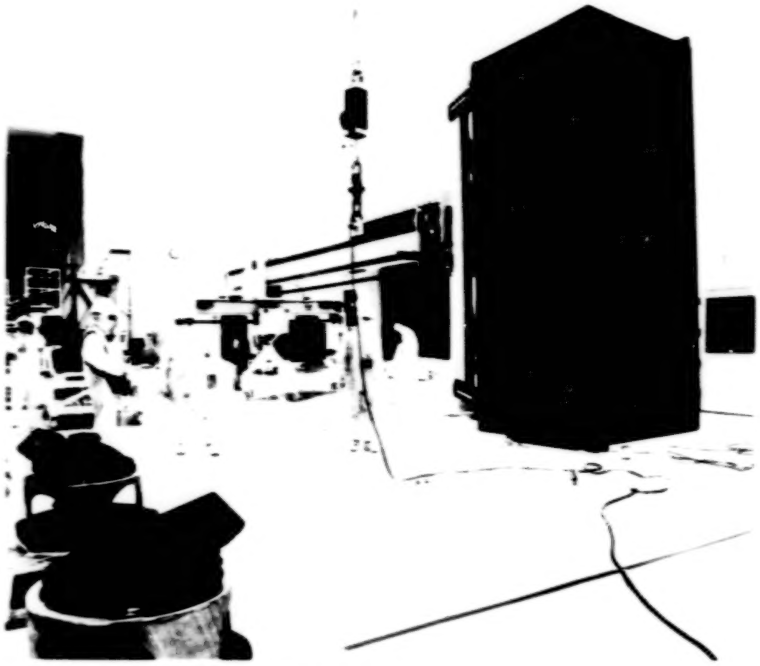
ORIGINAL PAGE IS
OF POOR QUALITY

The High Resolution Spectrograph will produce detailed ultraviolet spectra of celestial sources.

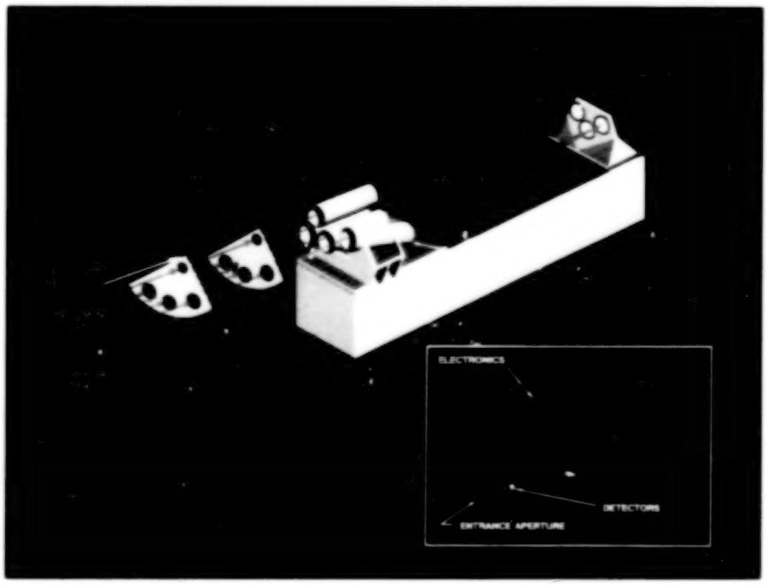
High Speed Photometer

The High Speed Photometer is the simplest instrument of the group; it has no moving parts and relies entirely on the pinpoint accuracy of the observatory's pointing system to pass the light collected by the telescope through the desired filter and aperture combination. After it receives radiation from a star or other source, the detector measures the intensity of the light in a particular spectral region. This instrument provides accurate measurements of the light from an object in space and can detect any fluctuations in brightness on a time scale down to microseconds. These measurements are made over a wide spectral range from visible to ultraviolet.

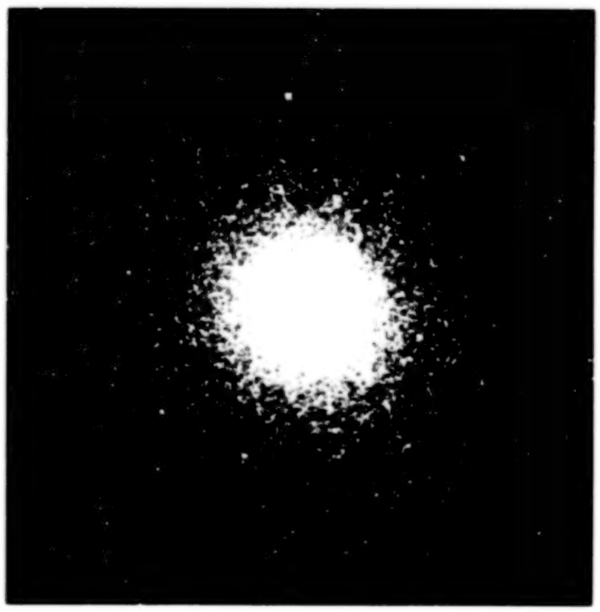
Earth's atmosphere limits some types of ground-based observations of a star's light variations to time scales of about one second or longer. This instrument is capable of making measurements as frequently as once every 10 microseconds, providing unprecedented time resolution of 20 microseconds. (One microsecond is one millionth of a second.) With this precise timer, the instrument can resolve the poorly understood rapid rotation, flickering, and oscillations that occur in white dwarfs, neutron stars, binary stars with gas streams, and pulsars. Measurements of flickering in accretion disks may make it possible to detect sites of black holes only a mile or two in diameter.



High Speed Photometer Installation Lockheed



The High Speed Photometer will precisely measure the brightness of objects in space.



Globular Star Cluster in Tucana
Cerro Tololo Inter-American Observatory

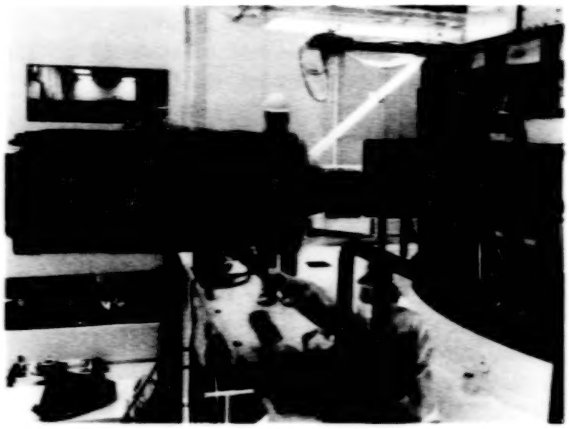
Fine Guidance Sensors

The main purpose of the three Fine Guidance Sensors is to provide the error signal for extremely good pointing stability, keeping the telescope still so the scientific instruments can produce unblurred, high-resolution images. Two of the sensors are sufficient to locate and lock onto a target without wavering; therefore, the third can be used for astrometry, to measure precisely the positions of other stars in the vicinity of the target.

The Fine Guidance Sensors can measure celestial positions 10 times more accurately than devices on Earth and, by triangulation, the distances of stars 10 times farther away can be mapped. A typical group of 10 stars can be mapped in a 10-minute period. With longer observing times, it will be possible to measure the distance of fainter stars, perhaps to magnitude 20.

The most accurate measurements of stellar distance are made by the method of parallaxes. The position of a star is measured relative to very distant background stars; then the measurement is repeated after six months when the Earth is at the opposite side of its orbit around the sun. The second observation usually reveals a slight shift in the apparent position of the star. This "parallax" results because the star was observed from different directions. Knowing the diameter of the Earth's orbit and the measured value of the parallax, astronomers can calculate the distance to the target star.

Ground-based telescopes can measure parallaxes to the desired accuracy of 10 percent only within 30 light years of Earth, or just a few thousandths of the diameter of the Milky Way. The Fine Guidance Sensors can measure stars with 10 percent accuracy at a distance of 300 light years. Within that range, there are many more stars and more types of stars to be observed.



Fine Guidance Sensor installation (Lockheed)

Second Generation Technology

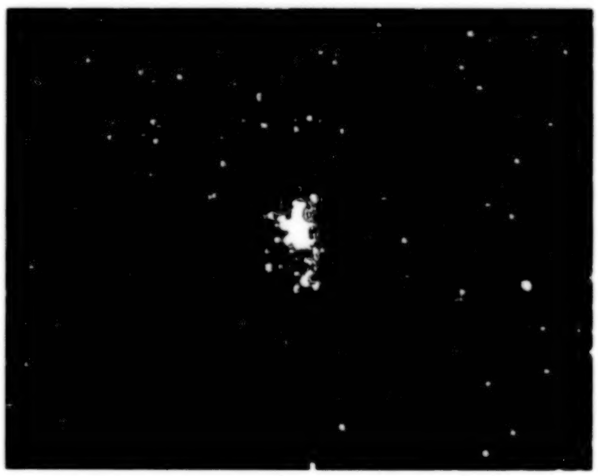
Like an observatory on the ground, the Hubble Space Telescope can adapt to new research priorities or new technology. New scientific instruments will be needed as the Hubble Space Telescope program matures.

Orbital servicing makes it possible to upgrade the telescope's capabilities by replacing focal plane instruments. Second generation scientific instruments already are being prepared for this substitution. Three instruments—an infrared camera/spectrometer, an advanced ultraviolet/visible light spectrograph, and an advanced Wide Field/Planetary Camera—have been selected for development. Once new instruments are approved for construction, they will be ready for installation approximately 5 years later. Refurbishment will be repeated periodically throughout the life of the observatory.

The Near-Infrared Camera/Multi-Object Spectrometer (NICMOS) will extend the telescope's capabilities into the infrared region of the spectrum. This instrument consists of three cameras and three spectrometers that can operate simultaneously. Detectors of mercury cadmium telluride will be used for best infrared sensitivity. Infrared observations give insight into the birth of stars and planets, as well as the composition of planetary atmospheres, planets, asteroids, and gas clouds. Clues to the "missing mass" of the universe may lie in the infrared spectrum. This instrument will be used to investigate many questions in planetary, galactic, and extragalactic science.

Another new instrument is the Space Telescope Imaging Spectrograph (STIS), which will cover a larger portion of the ultraviolet and visible spectrum with higher sensitivity and resolution than the two original spectrographs. This instrument will use two types of detectors: photon counters for ultraviolet observations and charge coupled devices (CCDs) for visible light. Its objectives include observations of star systems, galaxies, the interstellar and intergalactic medium, and phenomena in the solar system. This instrument should contribute to our understanding of high-energy objects, such as black holes and active galaxies.

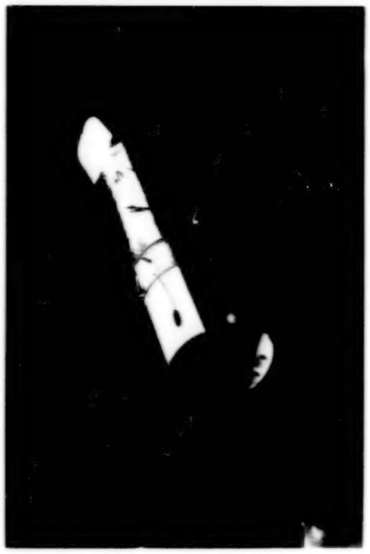
In addition, an advanced edition of the Wide Field/Planetary Camera (WF/PC-2) will replace the original instrument. Advances in CCD technology will permit higher resolution imaging by the second-generation instrument.



An infrared picture of the center of our galaxy shows many stars that are not visible at optical wavelengths because of dust between Earth and the galactic center. This picture was taken with prototype NICMOS detectors; white is the most intense radiation and blue the least intense. NICMOS will easily resolve the dense central region into individual objects to reveal whether the center of our galaxy is a black hole or a very dense cluster of stars. (University of Arizona)

Support Systems

Critical services that keep the telescope healthy and operating at peak performance are furnished by the equipment section of the Support Systems Module that encircles the primary mirror casing. Ten compartments house essential systems to provide power, pointing control, and communications functions. Access to these systems is through doors to the compartments.



Pointing and Control System

This system consists of a variety of elements that work together to control telescope maneuvers, pointing, and momentum management. The fixed head star trackers are used to point the telescope toward the general vicinity of an observation target. Six rate gyroscopes at the focal plane and three fine guidance sensors in the radial bays provide roll, pitch, and yaw information that keeps the observatory locked on a celestial object. The rate gyros are updated with information from the fine guidance sensors every second.

Actual telescope motions are controlled by varying the speed of four spinning reaction wheels. The signal for these wheels is derived from a variety of sources—a coarse sun sensor, fixed head star trackers, gyroscopes, and interferometric star trackers—all processed by the flight computer. Four magnetic torquer bars on the exterior work to maintain reaction wheel speed in an acceptable range. The telescope can be turned at a rate of 90 degrees in 18 minutes.

Spacecraft Power

The electrical power system generates power through the solar arrays, stores energy in the batteries, and distributes and controls energy delivered to the spacecraft. An average 2,400 watts are used to operate all of the subsystems and scientific instruments. Each instrument consumes only 110 to 150 watts of power, an amount no more than that used by a bright reading lamp.

Sunlight is converted to spacecraft power in the solar arrays attached to the telescope. When unfurled, the solar arrays measure 2.4 by 12.1 m (7.9 by 39.9 ft). The system is designed to supply the observatory with an average of 2,400 watts for more than 2 years after the telescope begins operations. This is sufficient to recharge the spacecraft's six batteries after it completes the nightside portion of its 96-minute orbit.

Solar Array

Thermal Protection

Temperatures inside the observatory are controlled actively by electric heaters and passively by interior insulation and exterior thermal coatings on the spacecraft. One side of the spacecraft seldom is exposed to the sun; subsystems requiring cool operating temperatures, such as the batteries, are located on this side.

Data Management

Hubble Space Telescope observations and operations are largely preprogrammed according to instructions sent to the spacecraft daily. The Data Management Subsystem and its central computer are the brain of the observatory. The triple-redundant computer processes and controls all information required to operate the spacecraft. Most commands are routed through, or stored in and executed by, the computer.

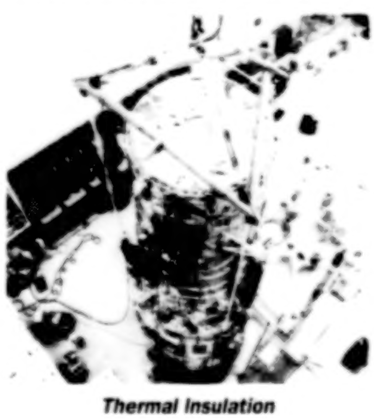
The Instrumentation and Communications Subsystem acquires onboard engineering data, transmits such information to the ground, and receives commands from the ground. These commands are processed and executed by the Data Management Subsystem.

The scientific instruments have their own Data Handling Subsystem. This computer accepts, decodes, and distributes commands to the detectors. It also puts scientific data into the proper format to be recorded and/or transmitted to Earth.

Scientific and engineering data are converted to electronic signals and transmitted via high gain antennas at rates up to one million bits per second. Upon reception, the data can be reconstructed into images and spectrograms by computer systems on the ground.

Safe Mode

The Hubble Space Telescope has built-in protection in case of problems in orbit. The primary threat to the telescope is loss of electrical power, so the basic strategy of the safe mode subsystem is to maintain pointing control and battery charging and to conserve power. There are various safe mode conditions.

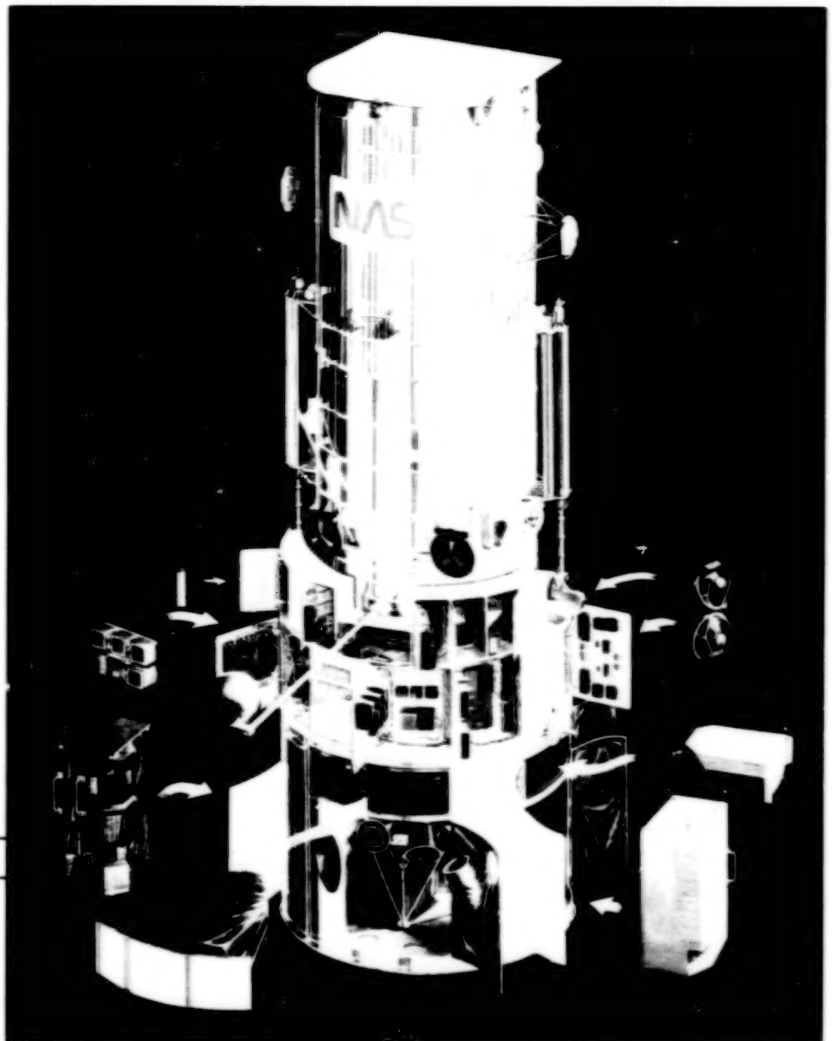


Thermal Insulation

The safe mode subsystem operates through the main computer or a special safe mode computer that automatically takes charge if the main computer fails. The safe mode subsystem is a perceptive watchdog, continuously monitoring critical parameters such as electrical power. If it detects an anomaly or failure, it "safes" the telescope, configuring and orienting it to guarantee adequate electrical power and giving the ground control team time to diagnose the problem and restore normal operations. For example, if the health monitoring system senses that the electrical energy in the batteries has fallen below a certain level, the safe mode subsystem turns the telescope to ensure full sunlight on the solar array. The safe mode computer, which deals with more serious problems, takes more stringent measures to ensure that critical components receive adequate power and reduces electrical power to components that are not essential to maintain the sun-pointing operation.

Aperture Door

When a problem has been diagnosed and remedied, ground controllers gradually restore the spacecraft to fully operational status. If a problem cannot be resolved by ground commands, the telescope will be maintained in a dormant condition until a Shuttle repair mission is mounted.



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Instruments, batteries, computers, and other essential components in the equipment bays are accessible through doors for easy removal and replacement. These items, called Orbital Replacement Units, are designed for servicing in space.

Hubble Space Telescope Chronology

1918	2.5 m (100 in) Hooker Telescope began operations at Mt. Wilson Observatory in Pasadena, California
1923	Hermann Oberth published Die Rakete zu den Planeträumen, speculating on telescopes in orbit
1946	Lyman Spitzer wrote an advanced study, Astronomical Advantages of an Extraterrestrial Observatory
1948	5.1 m (200 in) Hale Telescope dedicated at Mount Palomar
1958	NASA established; U.S. civilian space program initiated
1962	National Academy of Sciences published A Review of Space Research; Iowa study group recommended a Large Space Telescope as a national goal
1966	National Academy of Sciences published Space Research Directions for the Future; Woods Hole study group also recommended a Large Space Telescope
1968	1st Orbiting Astronomical Observatory launched for ultraviolet studies of stars
1969	National Academy of Sciences published Scientific Uses of the Large Space Telescope
1960's	Growing support and endorsement in the scientific community; growing acceptance of space astronomy as worthwhile endeavor; confidence increasing with early scientific results and technology developments
1971	Feasibility Studies (Phase A) for 3-m Large Space Telescope Large Space Telescope Steering Committee established
1972	2nd Orbiting Astronomical Observatory
1972–1977	Preliminary Design (Phase B) (1975: reduced to 2.4 m; European Space Agency involvement)
1977–1986	Development by prime contractors
1978	International Ultraviolet Explorer First space telescope with "real-time" control
1979	Astronauts began training with telescope mockup in Neutral Buoyancy Simulator
1981	Mirror completed
1983	Science Instruments delivered for testing at NASA; Space Telescope Science Institute dedicated; Space Telescope renamed Hubble Space Telescope;
1984	Optical Telescope Assembly delivered for assembly/integration
1984	Space Telescope Operations Control Center dedicated
1985	Integration of spacecraft completed
1986	Call for Proposals issued for observations
1986	Launch delayed after Challenger accident; ground tests continued
1986	Announcement of opportunity for amateur observing time
1990	Planned launch

Acknowledgements

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Graphic Design: O'Brien Graphic Design, Huntsville, Alabama

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APR 8 1991